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RESEARCHES ON PRELIMINARY CHEMICAL REACTIONS IN SPARK-IGNITION ENGINES

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RESEARCHES ON PRELIMINARY CHEMICAL REACTIONS IN SPARK-IGNITION ENGINES*

By E. Mühlner

Chemical reactions can demonstrably occur in a fuel-air mixture compressed in the working cylinder of an Otto-cycle (spark ignition) internal-combustion engine even before the charge is ignited by the flame proceeding from the sparking plug. These are the so-called "preliminary reactions" ("pre-flame" combustion or oxidation), and an exact knowledge of their characteristic development is of great importance for a correct appreciation of the phenomena of engine-knock (detonation), and consequently for its avoidance. Such reactions can be studied either in a working engine cylinder or in a combustion bomb. The first method necessitates a complicated experimental technique, while the second has the disadvantage of enabling only a single reaction to be studied at one time. Consequently, a new series of experiments was inaugurated, conducted in a motored (externally-driven) experimental engine of mixture-compression type, without ignition, the resulting preliminary reactions being detectable and measurable thermometrically.

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I. Influence of Preliminary Reactions on Engine-Knock

Reliable observations and theoretical analysis indicate that knocking (detonation) is produced in spark-ignition engines by the following causes [2]:-

On combustion being initiated by the ignition spark, a flame wave traverses the combustion space from the sparking plug and successively ignites all portions of the combustible mixture in the charge. In normal combustion no pressure-differences are set up by the passage of the inflammation wave, and all parts of the charge behave exactly alike.

In any case, the unburnt portions of the mixture charge are compressed by the expansion of the burnt gases; but in the case of knocking combustion (detonation), these unburnt portions self-ignite before the flame has reached them. The effect of this spontaneous combustion on the unburnt charge is instantaneous, and pressure-relief cannot take place. The pressure equilibrium in the combustion space is consequently disturbed, and pressure-equalization can take place only through the medium of shock waves and gas oscillations; these are the

cause of the knocking noise, and loss of power observed in the engine through the increased rate of heat transmission [2] 2).

The occurrence of detonation in an engine therefore depends entirely on whether self-ignition of the unburnt mixture takes place or not. This is controlled not only by the working conditions of the engine influencing the gas-state conditions in the cylinder through the variation in the rate of heat exchange, but also and principally, by the characteristic properties of the particular engine fuel. On the other hand, as indicated by the phenomenon of ignition lag - or, in chemical parlance, the finite induction time of the reaction - self-ignition is not a simple process: it is initiated and preceded by preliminary reactions ("pre-flame combustion") during which the complex hydrocarbon molecules are resolved into more easily - oxidizable simple radicals. Oxidation proceeds by chain reactions [3] and the branching of the reaction chains - i.e. an increase in the number of active particles participating in any partial reaction or link of the chain - can materially accelerate the speed of reaction. The chain reaction can be effected by the addition of anti-knock substances (dopes), e.g. tetraethyl lead. In knock-resistant (non-detonating) engine fuels, the preliminary reactions do not develop to the extent necessary for the initiation of self-ignition.

According to this theory of engine-knock, the determining factor is the development of preliminary reactions (oxidation) in the portions of the charge not yet reached by the ignition flame front. The study of these reactions in the combustion bomb or glass laboratory vessels is, however, attended by considerable difficulty, since they involve the production of a number of evanescent intermediates simultaneously present in the reactive mass, and difficult to separate; even the reactions between simple radicals are surprisingly complex [4]. Researches on a working engine with standard engine fuels are even more difficult, since these are mixtures of many different hydrocarbons, while the working conditions in an engine are not so controllable as the conditions of a laboratory experiment. In spite of this, the incentive to direct engine experiments is considerable, since direct and practically-useful results can be obtained by this means more quickly than by laboratory tests; in research on engine-knock in particular, application of experimental laboratory results to conditions in the actual engine, is too greatly dependant on accidental factors and the specific design and working characteristics of the engine.

Research on preliminary reactions by means of actual engine experiments has been conducted both with the help of controlled gas-sampling valves [5, 6, 7], etc. and by spectral analysis [6, 8]. Such experiments have shown that aldehydes and peroxides form in the unburnt charge to some extent even during the compression stroke; while even the least addition of peroxides to the mixture promotes knocking.

The drawing of gas samples from an engine combustion space is attended by considerable difficulties of a mechanical nature, and the resulting samples are not invariably satisfactory for the chemist.

Broeze, van Driel, and Peletier [9] indicate an alternative method, which has already been put intp practical use by Peletier; this consists of measuring the pressure-development and exhaust temperatures in a motored engine without ignition of the charge.

II: The Experiments of Peletier & Associates.

In Peletier's experiments [10] continuing earlier work by Mondain-Monval [11, 12], a C.F.R. knock-testing engine was used, motored at 900 r.p.m. by a swinging-field brake. The engine was charged with a fuel-air mixture preheated to 150° C, which was drawn in, compressed, expanded, and exhausted without ignition. The cooling temperature was 125° C. The pressure development in the engine cylinder was recorded by an optical indicator. The driving (motoring) torque of the engine was also measured:

The recorded diagrams show an extension of the expansion line indicating a pressure rise caused by the energy transformation in the preliminary reactions. This pressure-rise grew, up to an 80% excess of fuel over the stoichiometric ("theoretical") mixture ratio, while at still higher mixture strengths the effect disappears. The driving torque varied inversely with the mixture strength 3), attaining a minimum of 29 cmkg at a mixture-strength of 1.8 compared with 72 cmkg when running on air alone, i.e. a reduction of 60%. At 900 r.p.m. this would correspond to a power-output of 0.54 h.p. from the preliminary reaction ("pre-flame combustion") alone, without ignition of the charge. Since the C.F.R. engine is capable of developing 6 h.p., at this particular mixture strength about 9% of the energy in the fuel is transformed in the preliminary reaction.

When the mixture strength was increased beyond 1.8, the motoring torque did not, however, return to the value for operation on air alone. This was attributed by Peletier to a change in the specific heat owing to the increased richness of the mixture.

Preliminary reactions of sufficient intensity are usually accompanied by a faint, blue luminescence ("phosphorescence") in the engine cylinder.

These tests proved the existence of chemical action in the unburnt portion of the cylinder charge even prior to the passage of the spark, capable of assuming quite considerable proportions. Simultaneously, the "time-lag" of the process - i.e. the period from the initiation of the first reactions to complete inflammation of the charge - was found to correspond approximately to the total time available for combustion in the engine cylinder. The preliminary reactions can therefore be interrupted by the following expansion stroke, owing to the temperature drop in expansion, and the reaction products maintained in the state existing at that instant. Proof of this is afforded by the observation that the resultant pressure rise in the cylinder takes place already during the expansion stroke 4), - although the preliminary reactions are actually started by the adiabatic temperature rise during the compression stroke, i.e. at the latest at top dead-centre.

Subsequent experiments by Peletier indicated an influence exerted by the compression ratio: as could be anticipated, the extension of the indicator diagram representing the effect of the preliminary reactions, increases with the compression ratio; at the same time the hump in the expansion line is found nearer top dead-centre.

Since these tests were made with a standard fuel containing 70% iso-octane and 30% n - heptane, further experiments were made to determine the influence of fuel composition (characteristics). Increasing the proportion of iso-octane produced a continuous decrease in the pressure-gain along the expansion line of the indicator diagram; showing that, as might be expected the development of the preliminary reactions is restrained by an increase in the octane rating of the fuel. Tetra-ethyl lead likewise retards the preliminary reactions.

No luminescence was observed in the exhaust pipe, but the penetrating characteristic odour of the exhaust was unmistakable; the exhaust pipe became coated internally with an oily, viscous, brown deposit.

In a further experimental series Peletier used an air-cooled, two-stroke engine of 150 ccm., with electric heating elements fitted between the cooling fins. The compression ratio had a value of 6, and the change was preheated to 150° C. The curve of exhaust temperature against cylinder temperature had an irregular slope, whereas for a gaseous charge without chemical reactions, the corresponding curve is a straight line or of uniform curvature,- thus again demonstrating the occurrence of chemical reactions in the mixture, accompanied by luminescence at exhaust temperatures between 240 and 250° C, and again above 490° C.

The discharged mixture was chemically analysed, and the condensate found to consist of two separable components: one consisting principally of unmodified fuel with only a very small percentage of peroxides; the other water-soluble with about 5% by weight of peroxides. Since the water-soluble component constitutes about 10% of the total quantity of fuel in the mixture, the peroxides must form about 0.5% by weight of the latter.

III. New Experiments on Preliminary Reactions in the Engine

(a) Guiding Lines for the Experimental Investigation.

The experiments of Peletier and associates revived interest in the simple and effective method of investigation used by them. Although preliminary reactions of this type take place in any hot engine drawing-in mixture with the ignition cut off - as frequently occurs in motor vehicles negotiating steep gradients - and would be capable of detection and investigation in the indicator diagrams, by chemical examination of the exhaust gases, or, most simply, by measuring the temperatures in the exhaust pipe,- practical experiments have hitherto been almost exclusively carried out, either in the laboratory or on special knock-testing engines. While in laboratory experiments exact reproduction of actual working conditions is difficult, knock tests in the special engine involve limiting the mixture ratio within values assuring proper

ignition of the charge. But, as particularly demonstrated by the present series of tests, preliminary reactions are possible at mixture ratios far removed from the stoichiometric proportions; consequently examination of a wider range of mixtures would open up an entirely new and interesting field of research. The possibility of widely-varying mixture compositions and ratios, however, exists only if the normal process of ignition and inflammation in the engine cylinder is eliminated.

Peletier and his associates only dealt with a few experimental values out of the many possible mixture ratios; while the influence of this factor was duly investigated, their researches covered only the qualitative evaluation of the indicator diagram for a single mixture ratio. With one exception, their experimental fuels were simple mixtures of iso-octane and n - heptane.

Accordingly, the Engine Research Laboratory of the Hermann Goering Institute for Aeronautical Research, at the instance of E. Schmidt, conducted a series of experiments linking up with those of Peletier, but examining the whole question in greater detail, with the object of elucidating the connection between the preliminary reactions and fuel type, mixture ratio, engine speed, degree of compression, engine temperature and induction temperature, over a wide range of values.

The measure of the intensity of the preliminary reactions was assumed to be the measured temperature rise in the charge, which is simultaneously the principal variable factor in engine-knock. In order to eliminate the influence of variable engine friction or other insufficiently determinable variables, each test with fuel-air mixture was preceded by a reference test on pure air alone, and the temperature rise in the mixture charge, measured from the exhaust temperature of the pure-air charge; the induction temperatures for fuel-air mixture and pure air being the same. Indicator diagrams were taken of some of these reference tests.

(b) Experimental Technique

These experiments were made with the special fuel-testing engine [14], designed by the Research Laboratory for Motor Vehicles and Engines of the Stuttgart Technical College for Diesel fuel tests by the ignition lag method [13]. This engine has a widely-adjustable compression

ratio between 4.5 and 25; the cylinder and cylinder head are provided with a total of 4 boreholes, capable of accommodating quartz piezometer indicators, thermo-couples, quartz inspection windows, or other instruments. The engine and a swinging-field brake are mounted with all accessory equipment such as the lubricating and cooling systems, braking resistances, fuel tanks and gauges, on a common bedplate. The particulars of the engine are as follows:

Bore	:	101 mm.
Stroke	:	130 mm.
Swept Volume	:	1041 ccm.
Compression Ratio	:	variable
Running Speed	:	up to 2500 r.p.m.
Valve Timing	:	variable.

The standard valve timing used in the experiments was:

Exhaust opens	:	47° before L.D.C.
" closes	:	7° after T.D.C.
Intake opens	:	7° before T.D.C.
" closes	:	47° after L.D.C.

The intake and exhaust cams are of identical profile.

Carburettor : SUM carburettor with adjustable nozzles.

Swinging-field brake : Siemens-Schuckert Werke, type A.G.87. Separate excitation : 220 volts; armature test voltage : 400 volts; lever arm of the torque balance : 716.2 cm.

Lubricating oil : Aeroshell Medium
" " pressure : 2.4 at. gauge.

The quantity of lubricating oil in circulation was maintained constant at 6 litres during the tests.

The cylinder head and combustion space are shown in Fig. 1; they are of cast-iron, with internal cooling passages. The piston is a light-alloy forging with a flat top. Excluding certain shallow recesses, the combustion space has the general form of a flat cylinder. Intake and exhaust valves are identical; the valve ports have the usual form of a 90° elbow.

The engine was adapted for the present series of tests by careful alteration and adjustment of the induction and exhaust pipes, and the provision of suitable thermometers therein. The complete experimental installation is shown diagrammatically in Fig. 2.

1. Induction Pipe and Mixture Formation

The induction air enters at "A" from ducts under the laboratory floor, at a very uniform temperature, measured by the thermometer "B", and passes through the induction-air meter "C" working on the principle of a Roots blower, to the regulating chamber "D" of 0.1 m^3. From here the induction air proceeds along a pipe 65 mm. internal diameter and 700 mm. long surrounded by a 2 KW electric heater "E" connected to the laboratory electric supply, and a second heater "F" controlled by rheostat, to the carburettor "G". This is a SUM unit with adjustable nozzles; the sleeve type throttle is usually kept fully-open. Behind the carburettor the induction pipe has two 90° bends in which fuel droplets carried over with the mixture flow can be precipitated and prevented from influencing the thermometer "H" placed 850 mm. behind the carburettor. The induction pipe is thoroughly insulated between the carburettor and the engine, by aluminium foil and asbestos.

The intake and exhaust temperatures of the cylinder charge were measured by ordinary thermometers graduated to $\frac{1}{2}^{\circ}$, which were found by calibration to be entirely accurate within the standard reading error. Care was taken that the measuring point should project little beyond the pipe insulation, to eliminate correction for stem exposure the readings are, furthermore, used only to determine the temperature gradient or difference.

To enable the readings of the intake and exhaust thermometers to be properly averaged for time and pipe-section, and to suppress the influence of heat-radiation, these thermometers were placed in finned cups (probes) "J, K," Fig. 3, of light alloy insulated by fibre plugs and an air gap. Since the pipe was also insulated from the atmosphere and the cylinder head (which actually, however, had the same temperature as the pipe), its temperature was usually the same as the temperature of the mixture; the accuracy of the temperature-measurement may therefore be considered as within the limits of the reading error: i.e. $\pm 0.2^{\circ}$.

A second glass thermometer "L" was inserted naked in the pipe 60 mm. in front of the finned thermometer cup "J" for quicker regulation of the correct intake temperature owing to the quicker response of this instrument to sudden temperature variations.

The induction pipe includes a length of elastic Buna tubing to compensate for the vertical displacement of the engine cylinder at varying compression ratio. This elastic section survived the whole series of tests (about 625 running hours at 140° C and over).

2. Exhaust Pipe

The exhaust pipe is of the same internal diameter (65 mm.) as the induction pipe, and similarly insulated over a length of 900 mm. The exhaust thermometer "M" is of the same type as the intake thermometer, and placed in a similar finned cup "K". A branch from the exhaust pipe carries a test-cock "O" for sampling the exhausted mixture. The exhaust pipe also includes an elastic section for compensating the vertical displacement of the engine cylinder caused by variable compression ratio, and terminates in an outlet pipe "P" of 200 mm. diameter, through which air is drawn by the exhaust fan "Q". By this means the exhaust is diluted with a sufficient volume of air and cooled down to about 30° C, preventing any accumulation of a large volume of hot gases in the pipe, capable of easy ignition owing to the high proportion of simple radicals produced by the preliminary reactions in the engine cylinder. A further purpose of the exhaustor was to produce a slight under-pressure in the exhaust pipe: since resistance causes an under-pressure of about 180 mm. water in the induction pipe, it was thought advisable to equalize the pressures in the two pipes as far as possible, in order to avoid any disturbance of the scavenging. However, to attain this purpose completely, the exhaustor would have had to run at varying speed; in the actual case, attaining an under-pressure of 320 mm. water only with considerable throttling, the blower was inadequate for this purpose, but reference tests showed that with the existing very small valve overlap of only 2 x 7° crank angle, the influence of a slight pressure difference between the induction and exhaust pipes was negligible. Consequently, the complication of the experimental arrangement by the introduction of this pressure-regulating device was abandoned. The pressures in the

induction and exhaust pipes were measured by the U-tube water gauges "R" and "S".

No attempt was made to maintain a constant pressure in the induction pipe throughout the experiments; although in fact the induction pressure at the beginning of the compression stroke can materially influence the development of the preliminary reactions in the cylinder, as shown during these tests. The outside barometric pressure and any slight variation of the induction pressure with development of the preliminary reactions, consequently do, in fact, influence the experimental results to some extent. However, since the preliminary reactions are far more considerably affected by induction temperature and compression ratio, the effect of variable induction pressure will be of no practical importance.

3. Fuel Supply, Lubricating and Cooling Arrangements

The fuel consumption was measured as usual by means of a calibrated glass vessel, i.e. by volume. Since for economy of space this container had to be placed immediately over the hot engine, the temperature of the intaken fuel varied from 25-35° C. A thermometer "T" was placed in the side of the container, and the fuel weight consumed, calculated by reference to the specific gravity corresponding to the measured temperature. The mass-density of the fuel was measured by hydrometer.

The lubricating oil - Aeroshell medium - was cooled by a fresh-water circulating coil in the engine crankcase. The lubricating-oil pressure was maintained constant at 2.4 at. gauge, and the oil temperature, as measured by distant-reading mercury thermometer, maintained at 75° C. It may be assumed that the influence of these factors on the experimental values is very slight, since the fuel-air mixture can only come in contact with lubricant in the form of droplets adhering to the cylinder wall and head, which will have the same temperature as these masses. A constant lubricating oil temperature is of importance, however, with regard to its effect on the engine torque.

The coolant was ordinary, commercial ethylene glycol, since water-cooling would not have permitted of the temperatures necessary for preliminary reactions to develop. The coolant was circulated by means of a small centrifugal pump "W" driven by a separate electro-motor. The required

temperature of the coolant, and thus of the entire engine, was maintained by means of a fairly powerful electric heater "X" of 2 KW capacity, increased to 6 KW when heating up. The heating element was formed by first lagging the coolant pipes with asbestos board, on which a chrome-nickel resistance wire was wound, followed by aluminium foil with a spacing layer of loosely-spun asbestos cord. This type of insulation proved entirely satisfactory.

The temperatures at the coolant inlet and discharge were recorded by standard thermometers "Y" graduated to $1/10^{\circ}$ C. The readings were practically constant within 0.2° C, and the cylinder and cylinder-head temperatures may therefore be assumed sufficiently constant. The rate of flow of the glycol in circulation was about 0.2 kg/sec.

4. Motoring Mechanism

The swinging-field brake "V" used only to start-up the engine, had to be operated at an increased armature tension of 400 volts, since the external excitation of 220 volts was insufficient for high running speed. Two d. - c. generators in series were consequently used, and the armature voltage maintained constant by regulating the field excitation of the second generator: the current take-off by the brake armature was thus proportional to the engine torque.

The actual torque was measured by adjustable balance weights. Since the running speed was maintained at 1800 r.p.m. throughout the experiments, no allowance required to be made for the power-consumption of the exhaustor fan, the torque measurements being only comparative, and intended to furnish relative values.

5. Working Conditions and Notation

The experiments were designed to be run under unvarying working conditions as far as possible, and consequently the following constant values were maintained during all the tests:-

Lubricating oil temperature	=	75° C
" " pressure	=	2.4 at gauge
Coolant rate of flow	=	abt. 0.2 kg/sec.
Brake armature voltage	=	400
Valve timing	=	See Chap. II.b.

Since the majority of the tests were aimed at discovering the relationship between preliminary reactions, fuel-type, and mixture ratio, the following values and conditions were also maintained constant:

Engine speed - 1800 r.p.m.
Intake temperature of air and mixture - 140° C
Coolant temperature - 140° C
Under-pressure in induction and exhaust pipe: Induction throttle fully open Exhaustor fan running at constant speed.

The following notation was used for evaluating results and plotting curves:-

ϵ = compression ratio = $\frac{\text{Total Swept Volume}}{\text{Combustion space volume}}$

ϵ_ω = compression ratio corrected for valve lag past dead-centre.

$\Delta\epsilon = \epsilon - \epsilon_\omega$

Md (Kg) = Torque of the motored engine in terms of the weight on the lever arm of the brake.

ΔMd (Kg) = Torque decrement caused by the preliminary reactions.

n (r.p.m.) = Engine running speed

t_{La} (°C) = air exhaust temperature

t_{Le} (°C) = " intake "

t_{Ga} (°C) = mixture exhaust "

t_{Ge} (°C) = " intake "

$\Delta t_{GL} = t_{Ga} - t_{La}$ (°C) = Temperature difference due to preliminary reactions.

t_K (°C) = coolant temperature

G_B (Kg/sec) = fuel weight consumed

G_L (Kg/sec) = air weight consumed

m (Kg/Kg) = mixture ratio = G_L/G_B

m_{th} (Kg/Kg) = stoichiometric ("theoretical") mixture ratio

λ = excess air coefficient = $G_L/G_B \; 1/m_{th}$

β = mixture strength

t_v (^oC) = compression end temperature

X (mm) = piston travel

b_{ein} (mm^2 H_2 O) = difference of induction pressure to atmosphere

OZ = octane number (rated)

t (^oC) = any continuously varying temperature

p (Kg/cm^2) = " " " pressure

(c) Execution of the Experiments

The range of occurrence of thermometrically measurable preliminary reactions was delimited by initial tests, in which the most suitable standard working conditions were likewise determined, as given above.

A reference test on a pure-air charge was run before starting any test series, as soon as the engine had been run-in and temperature equilibrium established. It was found that at 1800 r.p.m., 140° C induction air and coolant temperature, and a compression ratio of 6, the temperature of the exhausted air was t_{LA} = 145° C. The exact value varied somewhat from day to day, probably owing to some slight irregularity in the running of the engine, and consequently had to be measured afresh on each occasion. At the beginning of the tests it was much lower-approx. t_{La} = 137° C. The probable cause of the variation was an impairment of the heat transmission between the piston and the cylinder wall with progressive

wear of the piston and rings, causing the piston-temperature to use; although measurements showed the piston-wear to amount only to 1/100 mm. reduction in diameter after 250 running hours.

The steady state only became established after the lapse of a certain time: usually 2 hours elapsed between first warming up and the first measurement on pure air. Each series of tests for any given running condition usually took about 45 mins. to complete.

After the exhaust temperature of the pure air charge had been determined, a progressively - increasing fuel charge was supplied, by opening the carburettor nozzles, the induction temperature being still maintained at $t_{Ge} = 140^{o}$. Owing to the initiation of preliminary reactions, the exhaust temperature now began to rise. The temperature difference was found by a separate test to be:

$$t_{GL} = t_{Ga} - t_{La}$$

In the curves accompanying this paper, the temperature difference is usually plotted against the mixture ratio.

The "excess air coefficient" λ was not used: besides being an inappropriate term [15], an "excess" of air is inapplicable by definition, where no combustion actually takes place. The process adopted in varying the running conditions being to add a continually-increasing volume of fuel to an approximately-constant volume of air, the value of the "mixture strength", defined as:

$$\beta = \frac{G_B}{G_L} . m_{th}$$

was found to be a more convenient factor; this increases with the proportion of fuel in the mixture, and for a stoichiometric ("theoretical") mixture has a value of unity. In the general case:

$$\beta = 1/\lambda$$

The minimum oxygen content, i.e. the stoichiometrically correct ratio for air, m_{th}, was determined analytically from the proportion of alcohols, olefines,

aromatics and dope in the fuel. The aromatic component was assumed to consist of benzole, as the most likely case. The stoichiometric ratio for the residual fuel (paraffins, olefines, etc., deducting aromatics and alcohols) was taken as: m_{th} = 15.0 kg.air/kg. fuel, - following "Hütte" 26.Ed. Vol. I, p. 575 for "Benzin". It will be recollected that the molecular weight has little influence on the value of the stoichiometric ratio, and the above assumption is therefore permissible. The mixture ratio for a fuel will then depend on its aromatic and alcohol content as found by chemical analysis.

The results of these investigations are summarized in Table 1. In this, (-) indicates that the particular value has not been determined, (0) that the component is absent in the fuel. The values for I.-G. standard reference spirit were furnished by the I.-G. Farbenindustrie themselves, who also kindly undertook the determination of the true octane value of some of the fuels indicated in the table by the column: "by I.-G. standard engine", and partially differing from the "nominal octane rating" or commercial octane value.

The compression ratio, which in the present curves is usually a parameter, is defined in the customary way as the ratio of the cylinder volumes at the two dead centres. Actually, of course, no compression takes place during the first part of the piston stroke since the inlet valve opens only at 47° crank angle after L.D.C. To be strictly correct, the compression ratio should therefore be reduced by a little more than 0.5 for values around 6, with the selected valve timing; but no notice has been taken of this in the present tests. In thermodynamical calculations, however, this adjustment to the true compression ratio should not be forgotten, and the value ϵ_ω used. Table 2 compares the compression ratio as conventionally stated, with the corrected true value for an exhaust-valve closing at 47° past L.D.C.

When the exhaust temperatures rose above 200-210° C by the effect of preliminary reactions in the charge, more or less heavy knocking (detonation) took place; usually starting in the exhaust pipe, but developing into the cylinder space with increased temperature of the mixture (whether due to the application of heat or increasing the compression ratio). In the exhaust pipe, detonation took the form of harmless explosions, but in the cylinder space it developed to a considerable extent, and

assumed the character of true engine knocking; although with the essential difference that the latter is caused by spontaneous combustion of the unburnt portion of the charge, while in the actual case of a motoring engine, practically the entire cylinder charge fired simultaneously.

Tests had to be interrupted when detonation set in, whether in the exhaust pipe or in the cylinder, since the generated heat raised the temperature of the exhaust pipe and the whole engine, and thus promoted spontaneous combustion of the following charges.

Even cutting off the fuel supply was of no effect, since the engine had to consume the fuel contained in the carburettor float chamber. Usually, the detonation in the cylinder increased considerably, and the engine commenced to run under power, with heavy knocking. The only effective remedy was usually, to motor the engine at a faster speed; an increase of 200 r.p.m. immediately suppressed self-ignition of the charge, indicating that it is caused by the same explosive reaction as detonation, since the latter can also be checked by increasing the engine speed, provided any increase in the engine load, and thus in the temperature, can be avoided.

Occasionally the engine ran under its own power, with the motoring drive cut out, without any knocking, entirely by the energy of the preliminary reactions.

No luminescence in the cylinder was observed through the quartz window provided [5]). Very weak luminescence, it is ture, might have been present as Peletier's experiments led one to expect - but was not observed since the quartz window very rapidly became dimmed by oil. On the other hand, insertion of the quartz window only after steady running had been established, would have entailed stopping the engine, with the loss of half an hour's time on re-starting and restoring steady-state conditions - by which time the quartz window would have oiled up again. Since the purpose of the tests was a quantitative analysis of the whole process, this individual development was not prosecuted.

To eliminate any possible effect of a difference in pressure between intake and exhaust pipes, the amount of valve lead was restricted to 2 x 7° crank angle; while to determine the effect of increased back-pressure in the

exhaust-pipe on exhaust temperature, the exhaust was slightly throttled in the pipe: the resulting temperature development agreed well with the temperature curve at normal exhaust pressure. The preliminary reactions will therefore not be materially affected by changes in the scavenging conditions.

Preliminary reactions may also be assumed induced by the heating of the mixture to intake temperature, and not solely by the heat developed in compression of the charge. Considering that the mixture takes a longer time to pass from the intake to the exhaust thermometer, than is available in the compression stroke alone, transformation of energy with the consequent temperature rise, can in fact take place without compression. This development would correspond approximately to Peletier's results (quartz-tube experiments [10]) or Mondain-Monval's preliminary tests [11], [12], which established the presence of reactions in the hot exhaust pipe of an overheated motor-car engine, although not usually in immediate proximity to the engine cylinder. In order to investigate this possibility, two cams of special shape were fitted, operating the valves at every revolution of the crank-shaft instead of every other, so that the engine worked in the manner of a plunger pump. No temperature difference was observed, whether running on mixture or on air. Apparently, therefore, the preliminary reactions are not induced by heating the intaken mixture to 140° C, either in the induction pipe or in the cylinder, even allowing for the relatively longer time the charge remains in the latter.

(d) Accuracy of Measurement

The endeavour to secure complete accuracy of measurement was restricted by the almost always indefinite and indefinable working conditions in the engine. Admittedly, in some cases the divergence between identical measurements in successive tests, is impossible to explain with any certainty: particularly the exhaust temperatures when running on pure air, which varied considerably from day to day, and increasingly with the progress of the tests. However, this temperature is obviously influenced by all the working conditions in the engine, and the maintenance of constant conditions, not only during a single test series, but throughout a lengthy experimental programme, is well-nigh impossible. The error can be compensated, however, by measuring the exhaust temperature separately in each test. The same inaccuracy is found in recording

successive torque measurements over any considerable period of time. It is fortunately possible, however, to attain greater accuracy in the case of the temperature difference Δt_{GL}, and the difference in torque running on mixture and on pure air. Uncontrollable errors are therefore largely eliminated in the determination of differential values. The induction air and mixture temperatures could be measured within $\pm 0.2^{\circ}$ C, and plotted accordingly. All other measured values were accurate within sufficient limits to avoid influencing the development of the preliminary reactions.

The attainable accuracy of measurement was consequently as follows:-

1. Reading error of the intake and exhaust temperatures in the individual test - $\pm 0.2^{\circ}$ C

2. Consequent possible variation in Δt_{GL} for the individual test - 0.4° C

3. Possible variation of Δt_{GL} over a series of tests, affecting the apparent error of the plotted curve - $0.6 - 0.8^{\circ}$ C

In particular cases the error was greater, but the reason was always detectable. If the resulting profile was a fair curve, however, the test was not always repeated.

4. Possible error of Δt_{GL} over a series of tests from irregular running of the engine - $1 - 2^{\circ}$ C

Accuracy suffered increasingly with increasing duration of the experimental programme, probably, changes in the fuel composition during storage, are responsible. In general, all experimental values were found accurate within not more than 2°, frequently, indeed, within 1° C.

5. Accuracy of the calculated mixture strength - $\pm 1/2^{\circ}$

6. Accuracy of torque - measurement - ±0.02 kg. (in terms of the weight on the lever arm).

7. The attainable accuracy of the plotted torque was only - ±0.1 kg, probably owing to fluctuations in the state of the lubricant. This does not, however, materially influence the other experimental values.

Generally speaking, the accuracy of the plotted curves is remarkable. Even the slope of the curves from the maximum at high compression ratios to nearly zero, was accurate in both directions, and uniform in result; the accuracy was greatest in the ascending branch, where the experimental points could be easily and correctly spotted.

(e) Experimental Results

1. Maximum Compression Temperature

The results are plotted in Figs. 5-17. For convenient estimation of the maximum engine temperature at any point on the curve, a separate diagram is given in Fig. 4, showing maximum temperatures at T.D.C. for any compression ratio [6] (on the assumption of adiabatic compression) and mixture ratio. These curves are calculated for octane, as the standard reference fuel in these tests, disregarding heat losses and using the specific heat ratios determined by G. Damköhler [18] for a temperature of 500° C, which are summarized in Table 3 for different mixture strengths.

The experimental curves show very considerable variation of compression end-pressure with mixture ratio. Owing to neglect of the heat losses, the true maximum temperatures in the cylinder will be higher than those stated.

2. Behaviour of Typical Aviation Fuels.

A typical development of the preliminary reactions was shown in the tests by Fuel No. 3 [7], a commercial grade of leaded aviation spirit rated 87-octane; see Fig. 5 [8]. Fig. 6 shows the same curves in extended represen-

tation, allowing the distribution of the experimental spots over the individual curves to be recognized. The scale of the ordinates commences for all curves at the zero point.

With increasing mixture strength β the curves of the temperature difference Δt_{GL} become steeper from the effect of the preliminary reactions, rising to a maximum before falling again, the steepness increasing with the compression ratio, and indicating almost instantaneous interruption of the preliminary reactions thereafter.

The experimental spots for maximum and disappearing preliminary reaction, however, are found to be displaced along the axis of the abscissae. Intermediate spots could not be plotted, since with increasing volume the flow through the cylinder becomes affected by the preliminary reactions: consequently, as soon as the steady state is attained, either the upper point is displaced to the left or the lower point to the right of the discontinuity in the curve.

The peak of the reaction moves with increasing compression ratio, towards a higher mixture strength, i.e. a richer mixture. Furthermore, in agreement with corresponding tests on other fuels, the ascending branches of the curves tend to "undercut" the curve below; in this region, therefore, the preliminary reactions decrease with increasing compression ratio, i.e. higher temperature.

The curves do not return to zero value at very high mixture ratios; whether this is due to reactions of a particular nature, or to a change in the conditions of heat transfer for the mixture or the pure-air charge, is as yet undecided.

The practically-useful compression ratio was restricted by the occurrence of spontaneous ignition. In the actual case, a complete curve could be plotted for $\epsilon = 7.5$, but no longer for $\epsilon = 8$, since detonation took place as soon as the exhaust temperature rose above about 200° C, corresponding to a value of Δt_{GL} of about 60° C; with increasing compression ratio, detonation takes place in even weaker mixture and at lower exhaust temperatures, although the general profile of the curve was the same. The curve for $\epsilon = 8.5$ could therefore be plotted only

down to $\beta = 1.0$. This displacement of the detonation limit was found in all fuels tested.

These curves show that the stoichiometric ("theoretical") mixture ratio is immaterial for the development of the preliminary reactions; as was to be expected, since the stoichiometric ratio aims at complete combustion, while in the actual case an excess of oxygen was always present, even in richer mixtures. Experiments such as Peletier's [10], made with a constant or stoichiometric mixture ratio, are thus incapable of fully disclosing the conditions in the engine cylinder.

To illustrate the considerable change in the curve profile with varying mixture ratio, Fig. 5 was replotted in Fig. 7. This form of representation plainly shows that the individual results for any particular mixture ratio can be applied to the general case only with the greatest caution, and may not even be characteristic of the particular working substance; although this will probably apply in a lesser degree to self-ignition tests such as carried out by Jost and Teichmann [16, 17].

Tests with other fuels show that the position of the peak is decisively affected also by the type of fuel used. The break in the curve, observed in the case of Fuel No. 3 (Figs. 5 and 6) only with a rich mixture, occurs in the case of Fuel No. 10 (Fig. 13) already at a mixture strength of $\beta = 1.0$. It is interesting to recall that an Otto-cycle engine attains only a mixture strength of round about $\beta = 1.0$ in operation. Engine-knock therefore consists of spontaneous ignition of a charge for which the conditions of reaction - in the sense of Fig. 5 - are to the right or left of the observed peak value.

Inspection of the results obtained with other fuels indicates that, as could be expected, the development of the preliminary reactions is intimately connected with the octane rating of the fuel: the higher the latter, the smaller the reactions. Curves could be plotted to show the temperature difference Δt_{GL} as a function of the octane rating against mixture strength and compression; but the values of $\Delta t_{GL} = f(\beta)$ to be used, will have to be taken indiscriminately to the right and left of the peak or break of the curve. The method has objections, and furthermore, despite the general validity of the relationship, individual fuel may exhibit reactions

disproportionate to their octane values, and deviate appreciably from the general case. An example is afforded by the three fuels Nos. 3, 4 and 5, all supplied under the designation of 87-octane aviation spirit. Firstly, complete curves were recorded for the Fuel No. 3 [10] (Aviation Spirit I), Figs. 5, 6 and 7. When the supply of No. 3 fuel was exhausted, it was found that the further supplies of ostensibly the same fuel (Aviation Spirit B.4), evidently had a lower octane rating, since the preliminary reactions were noticeably stronger. This new fuel was designated Fuel No. 4 (Aviation Spirit II), and subsequently tested by the J. - G. Farbenindustrie A. - G., in their knock-testing engine. The fuel was found to rate 88.1-octane. Unfortunately, no reference sample of No. 3 fuel had been retained from the first tests, so that its actual octane rating was unknown. The tests with No. 4 fuel were interrupted in the hope that yet further deliveries would reproduce the properties of the original No. 3 fuel. This third delivery, Fuel No. 5 (Aviation Spirit III, Table 1), however, showed even weaker reactions than No. 3, - see Fig. 8 [11]. Subsequent tests by the I. - G. Farbenindustrie A. - G. in the knock-testing engine, showed a relatively high rating of 90.6 - octane, explaining the weaker preliminary reactions, but comparison of Figs. 5 and 8 indicates that the divergence in the results is disproportionate to the difference of a little more than one unit in the octane rating (to judge from the relative intensity of the preliminary reactions, No.3 fuel must have been between 88.1 and 90.6 - octane, the corresponding values for Fuels Nos. 4 and 5), particularly when compared with Fuel No. 1 (58-octane, Fig. 11) and No. 2 (74-octane, Fig. 12). The general connection between high octane-rating and weak preliminary reactions will therefore be considerably modified, as anticipated, by the specific properties of the fuel, but the relationship remains essentially true, even as between leaded and unleaded fuels (Fuels Nos. 2 and 13, Fig. 12). Exceptions to this rule be referred to in due course.

3. The General Curve Profile

Not much can be said on the interpretation of the experimental curves, while any attempt at evaluation or prediction is at present excluded. It is only possible to establish the general relationships and the connection with previous work.

The increasing steepness of the curves proportionately to the mixture strength was in accordance with anticipations. It is equally obvious that the stoichiometric mixture ratio has no distinct effect on the curve profile since a considerable excess of oxygen is always present in the preliminary reactions:

The negative value of the temperature co-efficient visible in Fig. 7 ($\Delta t_{GL} = f(\epsilon)$) is, however, worthy of note. In the majority of cases after attaining its maximum the curve falls with increasing value of ϵ, i.e. increasing maximum charge temperature. The development is common to all fuels, although to a lesser degree at low octane ratings - see Fig. 11; however, the absence of a temperature relationship in the oxidation of hydrocarbons, in which chain reactions play such an important part, would have been remarkable.

A negative temperature coefficient was also found in other experiments on the oxidation of hydrocarbons (part [4], pp. 362, 422, 430, etc.).

The tests reproduced in Fig. 9, run at different mixture intake temperatures, also show the curves of higher intake temperature at first undercutting the lower curves. The absence of a similar development in the curves of Fig. 10, showing tests on the influence of varying coolant temperature, is probably due to the fact that the mixture entering the cylinder at 140° C, continues to gain or lose heat even after the end of the compression stroke without this further affecting the development of the preliminary reactions; but even in this case, the ascending branches of the curves remain close together.

Recalling the considerable influence of temperature on the development of the preliminary reactions, and the influence of varying mixture ratio (Fig. 4) on the resulting compression end-temperature, it will be realized that the development of the curve particularly the position of the break with increasing mixture strength, appears to be principally conditioned by temperature, and less by mixture ratio. Taking the corresponding compression end-temperatures for a number of spots on Fig. 5, from the curves in Fig. 4, and plotting them in Fig. 5, it will be found that the peaks of the curves indicate almost identical temperatures between about 385 and 405° C. The temperatures after the interruption of the preliminary

reactions, are also practically identical, at about 380° C. Proceeding along a curve of ϵ = const. towards lower mixture ratios, the temperature obviously increased.

In Figs. 8, 11, 13 and 14, the corresponding compression end-temperatures are plotted for a number of other fuels. It will be seen that the maximum values are all of the order of 390 - 400° C, irrespective of the type of fuel, and decrease only some 10 - 20° C after interruption of the preliminary reactions. The same development is shown in Fig. 9, where the same end temperatures are attained with varying intake temperatures. Only Fuel No. 10, Fig. 13, shows divergent results. Even though the temperature-drop of 10 - 20° C appears small, the rapid decrease of the preliminary reactions appears to be due principally to the decrease in the compression end-temperature; but the suddenness of the decrease at high compression ratios is still unexplained, while the explanation just given, is inapplicable to portions of the curve to the left of the peak.

Inspection of the attained values of the compression end temperature, indicates that at high compression ratios the temperature peaks must become displaced towards the right, since in a richer mixture the same end temperature is attained only with a higher compression ratio. The agreement of the peak values is so close that the position of any peak can be predicted. Simultaneously, it is now clear why the peak values increase directly with β, since in a richer mixture, a greater quantity of fuel is available for reaction.

4. Experiments on Different Fuels.

Effect of Leading

Fig. 11 shows the results obtained with Fuel No. 1, a 58-octane commercial "Standard petrol". As could be expected from the somewhat low octane-rating, the preliminary reactions develop to a considerable extent. Comparison with Figs. 5 and 8, representing experiments with approximately 87-octane fuel, justifies the following conclusions, already confirmed by experiment:

With decreasing octane rating, the ascending branch of the curve becomes steeper and straighter, and the degree of undercutting is less.

The curve for $\epsilon = 6.5$, Fig. 11 was interrupted by self-ignition of the charge at a mixture strength of $\beta = 1.25$. According to Fig. 4 this would correspond to a maximum compression end temperature t_v of 410° C. At this temperature, consequently, the fuel will have an induction time of less than one-eighth crank revolution, on the assumption that self-ignition can only take place with the piston near the top dead-centre, before the mixture has become cooled by expansion. Since at n = 1800 r.p.m. a semi-revolution lasts for about 0.0167 secs. (see also Fig. 22), the induction period, assuming it to continue for about 45° crank-angle, will correspond to about 0.0042 secs. This agrees in order of magnitude with Teichmann's results [17], who found an ignition lag of 0.005 secs for normal heptane at $\epsilon = 6$ and a compression end temperature of 677° abs. = 404° C ($\lambda = 0.8$, corresponding to about ($\beta = 1.2$). Normal heptane, having by definition an octane rating of 0, is of course more highly reactive than the 56.4-octane Fuel No. 1. The ignition lag shown by the present tests is therefore shorter than the theoretically-correct; but the difference can undoubtedly be explained by the fact that at the particular experimental point ignition had not yet taken place, while the stipulation of 45° crank-angle for the induction period is arbitrary.

Fig. 12 shows the results for Fuel No. 2, a 74-octane unleaded aviation spirit of commercial type, used in the preparation of 87-octane fuel by leading. Similarly to the tests referred to above, the preliminary reactions are of less intensity than shown in Fig. 11, the ascending branch is less steep, and under-cutting by the higher curves is less marked. The maximum temperature difference Δt_{GL} reaches 75° C. Assuming the calorific value of this particular fuel to be 10,000 Kcal/Kg, which would cause 15 Kg. of the mixture with a specific heat of 0.25 Kcal/Kg/°C to attain a temperature of about 2650° C, the temperature rise due to the preliminary reactions corresponds to about 3.5% of the total quantity of energy in the charge (calculated for the stoichiometric mixture). The effect of the preliminary reactions is thus quite considerable.

Fig. 12 includes curves for Fuel No. 13, prepared from Fuel No. 2 by the addition of 1.3 cm^3/litre "blue ethyl fluid" of the Ethyl-Gesellschaft (1.3 cm ethyl fluid corresponds to 0.85 cm^3 tetraethyl lead). As shown

by the analyses of Fuels Nos. 2, 3, and 4, this quantity corresponds approximately to the addition usually made for the preparation of 87 - octane aviation spirit from 74 - octane ordinary petrol.

Actually, a test of the resulting fuel in the I.-G. knock-testing engine, showed a true octane number of 87.8, agreeing very satisfactorily with the values for the series of aviation fuels of nominal 87-octane rating. The curve for this Fuel No. 13 should therefore closely resemble the curves for nominal 87-octane fuels at $\epsilon = 6.5$ shown in Fig. 5 or Fig. 8. On the other hand, as already stated above, Fuel No. 3 must have an octane-rating between Nos. 4 and 5, i.e. between 88.1 and 90.6, or little more than the value for Fuel No. 13; while Fuel No. 5 has an octane-rating of 90.6, i.e. appreciably more than Fuel No. 13. The preliminary reactions in Fuel No. 13 must therefore be rather greater than would correspond to Fig. 9 (Fuel No. 5). This is actually the case: at $\epsilon = 6.5$, Fuel No. 13 had temperature rise of $\Delta t_{GL} = 50^{\circ}$ C, Fuel No. 3 a value of 42° C, and Fuel No. 5 a value of 22° C. The influence of the octane rating on preliminary reactions is therefore quite considerable for similar fuels (i.e. prepared, as in the present case, by varying the proportion of tetraethyl lead, and the aromatic content).

Comparison of the curves for Fuel No. 13 (Fig. 12) with those for Fuel No. 2, shows that the addition of tetraethyl lead obviously has no material effect on the development of the curve. Such a diminution of the preliminary reactions, enabling the curve for $\epsilon = 6.5$ previously interrupted by the occurrence of spontaneous ignition (detonation), to be continued over the full range of mixture strengths, as well as the decreasing steepness of the ascending branch of the curve, were of course to be expected. Simultaneously the peak of the curve is displaced somewhat to the right. The curves for $\epsilon = 5$ show that the addition of tetraethyl lead reduces the magnitude of the preliminary reactions by about half.

Experiments on the effect of leading were also carried out with I.-G. standard reference fuel (called by the supplies: "I.-G.7" - Fuel No. 10), which had an octane rating of 44.6. The results of the comparative tests are shown in Fig. 13. The curve for the pure fuel, corresponding to its low octane-rating, is steep and

rises a considerable distance. The temperature difference reaches 66° C already at $\epsilon = 5$, and since lower compression ratios were impossible, further curves could not be recorded. The preliminary reactions are abruptly interrupted, without the curve forming a rounded hump, at a mixture strength below 1.0; a knock-testing engine running, as usual, on a stoichiometric ("theoretical") mixture ratio, therefore, never works within the region of preliminary reactions determinable by these means.

Fuel No. 10 was then tested with the addition of 1.35 cm^3 ethyl fluid, to determine the effect of leading. The results with this fuel (No. 12) are included in Fig. 13. In surprising contrast to previous experiments, it was found that leading had little or no effect; the shape of the ascending branch is unchanged, and the peak only slightly lower. To make sure that this unexpected result was not due to any peculiarity in the ethyl fluid used, Fuel No. 10 was treated with an equivalent (1 cm^3/litre) quantity of pure tetraethyl lead (Fuel No. 11). The results hardly differed, however, from those for Fuel No. 12 (Fig. 13).

According to a reference curve plotted by the makers, standard reference petrol with added 1 cm^3 tetraethyl lead per litre, should rate 74.5-octane. To check whether this rating was actually attained by the treatment, tests were made by the makers in the I.-G. knock-testing engine. The resulting values were 73.1 and 73.2 [12], proving that the added ethyl fluid and tetraethyl lead were of proper quality. Since this insensitivity of I.-G. standard reference petrol is in sharp contrast to the behaviour of other fuels, it must be a peculiarity of this fuel, to be explained by its high paraffin content. On the other hand, this fuel is particularly sensitive to leading when tested in the knock-testing engine. This surprising result is, however, paralleled by the experiments of Jost & Rögener [20] on self-ignition, who found no influence of tetraethyl lead on n - heptane (paraffinie). Since the present experiments have, however, definitely shown an influence of tetraethyl lead on preliminary reactions and self-ignition (Fig. 12), to the extent anticipated, the explanation for the divergence in the case of standard reference petrol must be sought in some peculiarity of fuel components of the paraffin series, behaving differently under actual running conditions (possibly under the influence of higher temperatures), than in experiments not

exactly reproducing engine working conditions. Actually, n - heptane is exceedingly sensitive to leading in regard to the engine octane-rating.

The tests with ordinary commercial fuels produced fairly uniform results; but it could be expected that the individual constituents, owing to their different chemical composition, would behave differently. To obtain information on this point, tests were made with pure iso-octane, ethyl alcohol, and benzol, all substances with a high octane rating: iso-octane, by definition, is 100-octane, alcohol, by Table 1, is approximately 99.5 - octane, and benzol is probably about 108 - octane.

In the case of benzol, no preliminary reactions of the present type could be detected, however much the compression ratio was increased or the experimental conditions varied, but self-ignition took place abruptly - already at 140° C mixture intake temperature and 1800 r.p.m., for a ratio of $\epsilon = 11$. Benzol therefore behaves similarly to the other fuels tested, self-igniting at a high compression ratio and either a very weak or a very rich mixture.

The absence of preliminary reaction in the case of benzol has been established also by other workers; particularly the fact that no peroxides are produced in benzol just prior to ignition (see [21], or [47] pp. 530 and 458, and [22], [24]).

Alcohol, on account of its high latent heat of evaporation, has a low mixing ratio and a high heat requirement, and consequently required an additional 2 KW heater on the experimental engine. It behaved similarly to benzol - no preliminary reactions could be detected prior to self-ignition. This result is, however, somewhat surprising.

The results of the tests with iso-octane (Fuel No. 7), are represented in Fig. 14. Comparing this with the curves already discussed, the considerable displacement of the curve into the rich-mixture region will be remarked: with mixtures three and a half times richer than the stoichiometrical ratio, the temperature increment is as much as 45° C. The compression ratios are high, corresponding to the high octane-rating. The slope of the ascending branch of the curve is small, the curvature of the profile considerable, and undercutting very marked. The breadth of the peak of the curve is also remarkable. Fig. 14 also shows comparative curves for experimental fuel No. 6,

which is a special 100-octane fuel with 40% aromatics, probably represented principally by benzol. The curve is plotted for a compression ratio of $\epsilon = 90$ and can therefore be compared with the curve for iso-octane, showing a temperature increment of 35° C. Since both fuels have the same octane rating, their preliminary re-actions may be expected to develop similarly; actually, no such similarity is to be found, probably explained by the fact that the benzol constituent of Fuel No. 6 retains some of its specific characteristics, even in the mixture.

5. Influence of Engine Working Conditions on the Development of Preliminary Reactions

Further experiments were made to determine the effect on the development of the preliminary reactions, of variation of the originally constant engine working conditions: e.g. intake and coolant temperatures, induction pressure, and engine speed.

Fig. 15 shows the relationship between the development of the preliminary reactions, and the pressures in the engine induction, for Fuel No. 2. The figures marked against the curves, represent over-or under-pressure in the induction pipe in terms of mm. water. It will be seen that the effect is the same as that of varying the compression ratio. The curves also show undercutting. The effect is, however, less with over-pressure than with under-pressure; this can be partially explained by a simultaneous change in the scavenging conditions. For the general case, however, variation of the induction pressure undoubtedly affects the development of preliminary reactions in the charge to a material degree. This conclusion, however, appears to contradict Teichmann's observation [17], that the effect of 1 at gauge on preignition of n - heptane was inconsiderable.

Fig. 10 shows the effect of varying coolant temperature, corresponding to the temperature of the cylinder wall. As expected, the preliminary reactions increase with the coolant temperature. The curves are particularly explicit in regard to the very great influence of the engine working temperature, and the consequent relationship between the occurrence of detonation and the temperatures of cylinder and piston.

Fig. 16 shows the influence of variable engine speed. It might have been expected that reducing the r.p.m., i.e. increasing the time available for reaction, would cause an increase in the temperature difference, but the extent to which this takes place is somewhat surprising. Reducing the r.p.m. by one-sixth already increases the temperature rise from 22° to 38°, i.e. by more than two-thirds. Already the curve for one-third reduction in r.p.m. (1200 instead of 1800 r.p.m.) could not be completed, since self-ignition set in. Increasing the engine speed therefore considerably reduces the preliminary reactions in the cylinder. It will be noted that this is also accompanied by a displacement of the peak value of the curve, but not by any undercutting.

The heat losses during the compression stroke counteract these influences. At higher engine speeds less heat is transmitted to the cylinder walls and the temperature of the charge consequently rises. If the temperature influence were to predominate over the time factor, the curves for higher r.p.m. should lie above those for lower r.p.m., contrary to observed.

Fig. 17 shows the very appreciable influence of the general engine working conditions on the development of the preliminary reactions, comparing the standard curve for Fuel No. 5 (n = 1800 r.p.m., t_K = 140° C., t_{GE} = 140° C) with curves for simultaneously varying engine speed, coolant temperature and mixture intake temperature. Small variations in these factors, have disproportionately great effect on the preliminary reactions; and the region of measurable reactions consequently requires careful determination. It is true that the experiments hitherto made do not indicate whether the same reactions will be measurable at considerably reduced temperatures and correspondingly higher compression ratios.

Fig. 9 shows the influence of mixture intake temperature for the case of Fuel No. 5. As anticipated, this influence is quite considerable and would be still greater in the absence of heat transfer to the cylinder wall, i.e. compensation of the difference between the mixture intake temperature and the cylinder wall temperature. The undercutting of the curves, corresponding to a negative temperature coefficient, is sharply defined. Here again, the curve peaks are displaced, evidently for the same reason as in the case of increasing compression

ratio; i.e. the same compression end-temperature results from a greater temperature-increment (compared with standare t_{Ge} and ϵ) in a richer mixture.

Fuel No. 5 was also tested for the influence of variable oxygen content of the mixture; the results are shown by the dotted curve in Fig. 8. In the first test, the normal oxygen content of the induction air was doubled, i.e. increased to 46% by weight. The resulting detonations were so powerful that the oxygen supply had to be promptly cut down to an excess of 14.5% by weight; the total oxygen content of the mixture, neglecting any oxygen in the fuel, was consequently reduced to 37.6% by weight. The peak of the measured curve was then at 33° instead of 22° C, at the same compression ratio of $\epsilon = 6.5$. The increase in the peak value was consequently 50%, for an excess oxygen content of $\frac{37.6 - 23.1}{23.1} .100 = 63\%$

The nitrogen content of the combustion air consequently does not appear to have any perceptible influence on the development of the preliminary reactions.

This was, as a matter of fact, the only test in which the peak value rose without a simultaneous displacement along the abscissa. The mixture strength β is referred to the actual oxygen content of the mixture.

6. Indicator Diagrams

For some tests, the development of the preliminary reactions was recorded by means of indicator diagrams. The indicator gauge was a Gohlcke-LFA quartz piezometer working the loop of a Siemens oscillograph through an amplifier. The time marks were spaced 1/500 sec., and the top dead centre separately registered on the diagram by means of an interruptor working on a third loop. The loop was deflected at 30° crank-angle before T.D.C.

The indicator diagrams are reproduced in Figs. 18-21; of these, Figs. 18 and 19 represent the 74-octane Fuel No. 2 without the addition of tetraethyl lead, - Fig. 18 at $\epsilon = 5.5$ and 900 r.p.m., Fig. 19 at $\epsilon = 6.5$ and 1800 r.p.m. A direct influence of the r.p.m. value, i.e. of time, on the development of the diagram was not observed. It might be expected that at lower speeds the hump visible on the line will move closer to T.D.C.

Fig. 18 shows a perpendicular line drawn through the position of T.D.C., representing the axis of symmetry in the absence of preliminary reactions, and clearly demonstrating their considerable development.

The most interesting indication afforded by the diagram, is that the development of the reactions differs in succeeding working cycles of the engine. Usually, detectable preliminary reactions take place on about every second working stroke. Fig. 19 shows that in two cases there have obviously been no preliminary reactions, while in one case they have apparently developed only half-way through the piston stroke.

This divergent behaviour can be explained with comparative ease by the assumption that the (presumably small) number of reactive particles remaining in the residual charge in the cylinder, varies in successive strokes of the piston, and therefore variably affects the development of the preliminary reactions in the ensuing engine cycle. It is of interest to note that consequently, a temperature rise of 75° C in the cylinder charge, such as has been observed in certain cases, takes place within about half the working stroke - i.e., during a working stroke accompanied by considerable preliminary reactions, the temperature within the cylinder may rise by about 150° C - without leading to self-ignition.

The diagrams agree generally in showing the energy transformation of the preliminary reactions as occurring immediately past T.D.C., i.e. when the compression temperature is at its maximum. This again points to the experimentally-proved fact that the preliminary reactions are intimately bound up with the temperature development in the charge. On the other hand, since the reactions are interrupted by the expansion of the charge, the energy-transformation will not develop to the full extent as soon as the effective temperature is attained; but an increase in the time spent by the charge in the cylinder will immediately lead to very rapid ignition. The reactions are thus easily controlled by the engine speed and the compression ratio - i.e. temperature - and the possibility of self-ignition therefore appears excluded. "Back firing" of this type was not observed in any of the tests.

Fig. 20 shows the diagrams for Fuel No. 13, i.e. the same fuel as in Figs. 18 and 19, but after the addition of tetraethyl lead. It will be observed that the characteristic humps have entirely disappeared, and the transition between the compression and expansion lines is a smooth curve.

Correspondingly, the indicator diagram reproduced in Fig. 21 for Fuel No. 3, treated with tetraethyl lead, also shows no humps, although the measured temperature peak rose to 59° C. While all untreated fuels show a small, rounded, continuously-wavering peak to the right of T.D.C., clearly apparent on the indicator screen for fuels treated with tetraethyl lead the curve is almost completely smooth and steady, with only slight irregularity in the expansion line. This difference in behaviour was always clearly visible on the indicator screen. However, this difference in the behaviour of leaded and unleaded fuels can be balanced by adjusting the temperature-pressure relationship to produce an identical temperature increment. Thus, in the test shown on Fig. 20, Δt_{GL} = 50° C was obtained with $\beta = 1.4$, which agrees well with the curve shown in Fig. 12.

This specific effect of the addition of tetraethyl lead is detectable solely from the indicator diagram. In other respects, the behaviour of leaded fuels at corresponding (usually higher) compression ratios, usually did not differ, particularly with respect to the value of the temperature-rise and the possibility of self-ignition, from the behaviour of untreated fuels.

The leaded fuels must obviously have a higher expansion line in the indicator diagram: a development in the opposite direction is impossible, since the pressure in a constant volume of gas increased only with temperature. Unfortunately, the accuracy of the indicator diagrams and the position of the dead-centre markings was insufficient to enable the extent of the pressure-rise to be numerically evaluated.

However, it proved possible to make a numerical evaluation of the pressure and temperature development, neglecting the heat losses, for the indicator diagram Fig. 19, at $\beta = 1.60$, $\epsilon = 6.5$, and the usual value-timing (i.e. with ϵ_ω). The results are shown in Fig. 22. It will be seen that the temperature rapidly attains the maximum, and sinks likewise very quickly. In any case, the maximum temperature persists over only about 15° crank-angle or, at 1800 r.p.m. and using the time scale on the figure, for about 1.3×10^{-3} sec. - with an approximation sufficiently accurate in the case of chemical reactions. It can therefore be assumed that reactions beginning before T.D.C. are negligible.

Fig. 23 shows the third indicator curve of Fig. 19 replotted as a pressure-path curve, showing that the pressure-rise caused by the preliminary reactions is quite considerable, even by this method of representation, adopted, shows with particular clarity that the pressure peak does not occur appreciably after T.D.C., as would be the case for pronounced ignition lag in the engine.

7. Torque Measurements

These indicator diagrams explain why the development of perceptible energy in the running engine can be measured on the diminution of the motoring torque required by the engine. Denoting the difference in torque between running on pure air and running on mixture, by ΔMd, it will be found that this difference is usually approximately proportional to the measured temperature difference Δt_{GL}. Fig. 24 shows the torque difference (expressed in Kg weight applied to the lever arm of the swinging field brake) for the conditions represented by Fig. 5. For $\epsilon = 6.5$ the ordinate scale is likewise graduated for the absolute torque value Md, this graduation being strictly correct only for this particular value of $\epsilon = 6.5$.

Comparing Figs. 24 and 5, it will be seen that the curve of the torque difference is practically the inverse of the curve of the temperature difference; the torque minimum, in particular, is at the same point as the temperature maximum. It is worthy of mention that Peletier [10] plotted such a curve of torque variation for a constant compression ratio and a single fuel, but these results are not decisive for the general case.

8. Chemical Analysis, Luminescence

In one experiment (with Fuel No. 3) a portion of the exhaust gases was drawn off and led through traps cooled by liquid air. The chemical analysis of the mixture thus collected, was performed by G. Damköhler and W. Eggersglüss, and gave the following results: Per mol of fuel (reduced to n - heptane) - abt 0.141 mol aldehydes, 0.024 mol acids, 0.05 mol alcohols, 0.001 mol peroxides, 0.045 mol carbon dioxide, and 1.1 mol water. 0.084 mol of the aldehydes was in the form of formaldehyde. A more detailed report on this analysis will be found in [25].

In all the tests, the characteristic, penetrating odour of the exhaust was observed; the exhaust pipe speedily became coated internally with a brown, oily deposit, which did not, however, appear to consist entirely of lubricating oil. The possibility of the latter directly affecting development of the preliminary reactions, on the assumption of greater reactivity of the lubricating oil compared with the fuel, was investigated by running tests with a deficiency and a considerable excess of lubricant; but without establishing the presence of any such influence.

Luminescence of the charge was observed through the quartz window fitted in the engine cylinder, on only one occasion.

In this solitary case, a special fuel was being used, normally employed as a starting (pilot injection) fuel for Diesel engines [13], with an octane rating well below zero. At $\epsilon = 5.0$, intake temperature $t_{Ge} = 110$ C [14], and a very considerable development of the preliminary reactions, faint, bluish luminescence was observed in the cylinder, of the type already noticed by Peletier [10]. Simultaneously, the exhaust had a particularly penetrating odour.

IV Conclusions from the Engine Tests

The investigation was intended to obtain an insight into the development of preliminary reactions in an Otto-cycle (spark-ignition) engine, with particular reference to the relationship between them and the mixture ratio and engine working conditions. The range of the experiments was, however, incomplete, lacking in particular, reference tests at low intake temperature and correspondingly increased compression ratio, as well as further tests with different fuels. For the first object, it would appear necessary to extend the experiments to low-octane fuels, following the line indicated by the results obtained with the pilot-ignition (accelerator) fuel mentioned in the preceding chapter.

Furthermore, it would be of interest to extend the experiments to fuels of particularly high chemical purity, as the only means of obtaining completely accurate reference values. In fact, determination of the individual influence of aromatics, olefines, paraffins, would only be possible by this means.

In general, there are still many fields of application still open to this method of research; although materials of the requisite purity may be expensive and difficult to obtain in the quantities necessary for a complete engine test - about 20 litres per curve recorded, or 150 litres for a complete series. An engine of particularly reduced dimensions should therefore be made available for such experiments.

Research should concentrate now principally on chemical analysis of the reaction products of simple fuels; for which purpose this particular experimental technique is preferable to the use of explosion bombs, since the oxidation products can be cumulatively concentrated. The methods of analysis, however, must be of the highest accuracy.

Originally, although only as a secondary objective, it was intended to use this method for determining the octane rating of engine fuels. This will be difficult, however, owing to the very divergent behaviour of certain fuels, which would appear to be due to the behaviour of their olefine and paraffin constituents. On the other hand, these experiments have shown the very close relationship between the temperature increment of the mixture charge and the octane rating of the fuel; particularly in the case of low-octane fuels and in some aviation fuels where relatively small variations in the octane number have produced disproportionate effects on the temperature movement. Consequently, the possibility of eventually applying this method to the determination of fuel octane-rating is by no means excluded, provided standard working conditions (which would have to be formulated) are rigorously maintained. The method would then be even more suitable than the use of the knock-testing engine, since the bouncing-pin indicator, always a fertile source of errors, will be eliminated and the octane rating obtained essentially by direct temperature measurement only. If disturbing influences can be controlled or avoided, the method should prove highly accurate.

V. Summary

The description of an experimental method for investigating the preliminary reactions occurring in the working cylinder of an Otto-cycle, spark-ignition engine in which the combustible mixture is induced into a motored

experimental engine. The reactions taking place in the charge in the absence of ignition, are found to produce a measurable temperature rise in addition to subsidiary effects. The temperature increment is found to depend greatly on the mixture ratio, fuel properties - particularly the octane rating - and the working conditions in the engine, notably the temperature development in the cylinder. The results are reproduced in the form of curves, and the further possibilities of the method discussed in detail.

VI. Bibliography

[1]. Physikalische und chemische Vorgänge bei der Verbrennung im Motor. Deutsche Akad. Luftfahrtforschung, no. 9.

[2]. Schmidt, E.: Uber das Klopfen und die damit verbundene Verminderung des Wirkungsgrades von Otto-Motoren. Deutsche Akad. Luftfahrtforschung, no. 9, pp. 215-230.

[3]. Eucken, A.: Grundsätzliches über den Zerfallmechanismus einfacher Kohlenwasserstoffe. Deutsche Akad. Luftfahrtforschung, no. 9, pp. 93-112.

[4]. Jost, W.: Explosions - und Verbrennungsvorgänge in Gasen. Julius Springer (Berlin), 1939.

[5]. Egerton, C. G.: Das Klopfen und die Kohlenwasserstoff-Verbrennung. Deutsche Akad. Luftfahrtforschung, no. 9, pp. 173-182.

[6]. Boyd, T. A.: Untersuchungen über die Flamme im Motor. A.T.Z., vol 43, no. 3, 1940, pp. 51-62.

[7]. Egerton, C. G., Smith, and Ubbelohde: Phil. Trans. Roy. Soc. London, A. 234, 1935, p. 433.

[8]. Withrow and Rassweiler: Ind. & Eng. Chem. (Ind. Ed.), vol. 25 (1933), p. 1359; vol. 26 (1934), p. 1256; vol. 27 (1935), p. 872.

[9]. Broeze, I. I., van Driel, H., and Peletier, L. A.: Betrachtungen über den Klopfvorgang im Ottomotor. Deutsche Akad. Luftfahrtforschung, no. 9, pp. 187-208.

[10]. Peletier, L. A., van Hoogstraten, S. G., Smittenberg, I., and Kooymann, L. P.: Reactions chimiques prealables dans un moteur à essence. Chaleur et Industrie, vol. 20, 1939, pp. 120-125.

[11]. Müller, K. O.: Stand der experimentellen und wissenschaftlichen Kenntnisse der Oxydation von Kohlenwasserstoffen und das Phänomens des Klopfens in den Verbrennungsmotoren. A.T.Z., vol. 35, 1932, pp. 597-600.

[12]. Mondain-Monval, C. R.: Comptes Rendus, Acad. des Sciences, vol. 189, 1929, p. 1195; vol. 191, 1930, p. 299.

[13]. Ernst, H.: Über die Prüfung von Dieselkraftstoffen. A.T.Z., vol. 42, no. 8, April 1939, pp. 213-221.

[14]. Schmidt, P.: FKFS Fuel Testing Station. Neue Kraftf.-Z., vol. 13, no. 4, 1938, pp. 79-80.

[15]. Mühlner, E.: Luftverhältniss, Brennstoffverhältniss, Verdichtungszahl. A.T.Z., vol. 44, no. 3, 1941, pp. 52-53.

[16]. Jost, W.: Reaktionskinetische Untersuchungen zum Klopfvorgang. Z. Elektrochem., vol. 47, no. 3, 1941, p. 262.

[17]. Teichmann, H.: Reaktionskinetische Untersuchungen zum Klopfvorgang, II. Z. Elektrochem, vol. 47, no. 4, 1941, p. 297.

[18]. Damköhler, G.: Gasbewegung in einem geschlossenen Verbrennungsraum bei einseitiger Zündung. Jahrb. 1938 der deutschen Versuchsanstalt für Luftfahrt, R. Oldenbourg (Munich), pp. II 62-75.

[19]. Jost, W., and Von Müffling: Studies on the Kinetics of Reaction in Engine Knock. Z. Elektrochem, vol. 45, no. 1, 1939, pp. 93-100.

[20]. Jost, W., and Rögener: Studies on the Kinetics of Reaction in Engine Knock, III. Z. Elektrochem, vol. 47, no. 4, 1941, p. 307.

[21]. Egerton, C. G., Smith, and Ubbelohde: Phil. Trans. Roy. Soc. London, vol. 234, 1935, pp. 433-521.

[22]. Ubbelohde, Drinkwater, A. R., and Egerton, A.: Phil. Trans. Roy. Soc. London, ser. A, vol. 153, 1936, p. 103.

[23]. Jost, W.: Die physikalisch-chemischen Grundlagen der Verbrennung im Motor. Motor und Kraftstoff. VDI (Berlin), 1939, pp. 50-58.

[24]. Pye: Internal-Combustion Engines. 1933.

[25]. Damköhler, G., and Eggerglüss, W.: Reaktionsprodukte eines im Motor kurzzeitig komprimierten aber nicht gezündeten Benzin-Luft-Gemisches. Z. phys. Chemie (B), vol. 51, 1942, pp. 157-186.

Footnotes:-

1) Cf. e.g. Physical & Chemical Phenomena in Engine Combustion. Papers and Discussions at the 5th General Meeting of the German Academy for Aeronautical Research, 10-11 May 1939. Pub. Schriften der deutschen Akademie der Luftfahrtforschung, no. 9.

2) Figures in square brackets refer to the bibliography at the end of the paper.

3) Mixture Strength = ratio of actual quantity of fuel to the quantity required for stoichiometric combustion.

4) Cf. Figs. 18-21 in this paper.

5) For one exception see Chap. III e.8.

6) The actual compression ratio according to Table 2 was applied in the calculation, but the usual coefficient entered on the diagram.

7) The fuel numbers correspond to Table 1.

8) The figures accompanying the curves (Temperatures in °C) will be discussed presently.

9) Fig. 6 includes the measured spots, omitted in Fig. 5 for the sake of clarity.

10) The numbering of the fuels refers to Table 1. The three grades of aviation spirit are also denoted by I, II, III, in the order of their use.

11) The dotted curves in Fig. 8 represent tests with excess of oxygen - see Chap. III. e.5. The figures on these curves are temperatures in °C. See succeeding chapter.

12) As a matter of fact, the curve for fuel No. 12 with an octane rating 0.1 higher than No. 11, is by the obvious amount of 4° C higher.

13) Predominantly paraffinic with long, unbranched chains.

14) I.e. 30° C less than in the other tests.

Translation by L. T. Goodlet,
Issued by the Ministry of
Aircraft Production, London.

Fuel number	Fuel designation	Octane number		Percentage by volume						Stoichiometric mixture ratio m_{th} kg.air/kg.fuel
		Nominal rating	By I. G. standard oo engine test	Alcohol	Olefines	Paraffins	Aromatics	Naphthenes	Tetraethyl lead	
1	Commercial "standard" petrol	58	56.4	0	8	---	7.3	----	0	14.88
2	Unleaded aviation petrol	74	72.0	0	5	---	4.1	----	0	14.94
3	Aviation spirit I	87	----	----	3	---	17.0	----	0.07	14.71
4	Aviation spirit II	87	88.1	----	4	---	9.0	43.7	0.08	14.85
5	Aviation spirit III	87	90.6	----	3.5	---	8.5	44.2	0.09	14.86
6	Special spirit	100	----	0	2	---	40.0	----	0.08	14.32
7	Pure iso-octane	100	----	0	0	100	0	0	0	15.18
8	Ethyl alcohol	99.5 [4]	----	99.9	0	0	0	0	0	9.04
9	Benzole, technically pure	108 [5]	----	0	0	0	100	0	0	13.33 [7]
10	I.-G. Standard Reference Fuel (I.-G.7) [6]	44.6	44.6	0	0.6	77	2.4	20.0	0	15.0
11	I.-G. Standard Reference Fuel + 1 cm^3/ $P6(E)_4$ [1]	74.5 [2]	73.1	0	0.6	77	2.4	20.0	0.1	15.0
12	I.-G. Standard Reference Fuel + 1.53 cm^3/ Ethyl [1]	74.5 [2]	73.2	0	0.6	77	2.4	20.0	0.1	15.0
13	Fuel No. 2 + 1.3 cm^3/ Ethyl [3]	87	87.8	0	5	---	4.1	----	0.085	14.94

(Footnotes).

1) 1 cm^3 $P6(C_2H_5)_4$ are contained in $\frac{1}{1.53}$ cm^3 = 0.655 cm^3 ethyl fluid.

2) According to I.-G. Curve TprS.883a.

3) 1.3 cm^3 ethyl fluid contain 0.85 cm^2 Pb $(C_2H_5)_4$. This is the usual percentage for aviation spirit.

4) According to W. Jost.- Detonation and combustion in Gases , Berlin 1939, p. 550.

5) Extrapolated from data of the I.-G.

6) Information supplied by the I.-G.

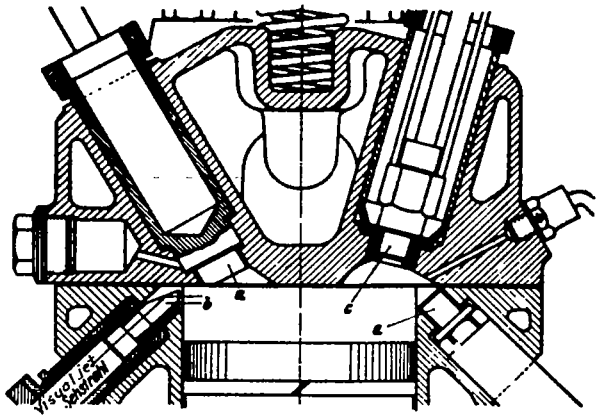
7) For technically-pure benzole (with admixture of tolnol).

8) Tested in the I.-G. engine.

ϵ usual notation	5.0	5.5	6.0	6.5	7.0	7.5	8.0	9.0	10.0
$\Delta \epsilon$	0.478	0.538	0.598	0.658	0.717	0.777	0.837	0.956	1.076
ϵ	4.522	4.962	5.402	5.842	6.283	6.723	7.163	8.044	8.924

3. Values of the compression exponent for a mixture with the mixture-strength

β	0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0
x	1.360	1.322	1.298	1.274	1.252	1.239	1.225	1.211	1.200



(a) Blank plug
(b) Quartz observation window
(c) Quartz piezometer gauge

Figure 1.- Cylinder head of the experimental engine.

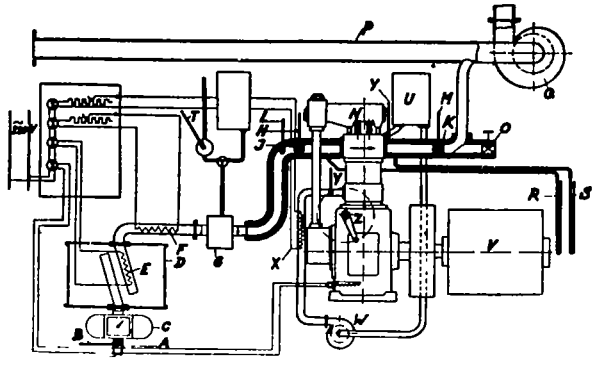


Figure 2.- Experimental arrangement; for notation see text.

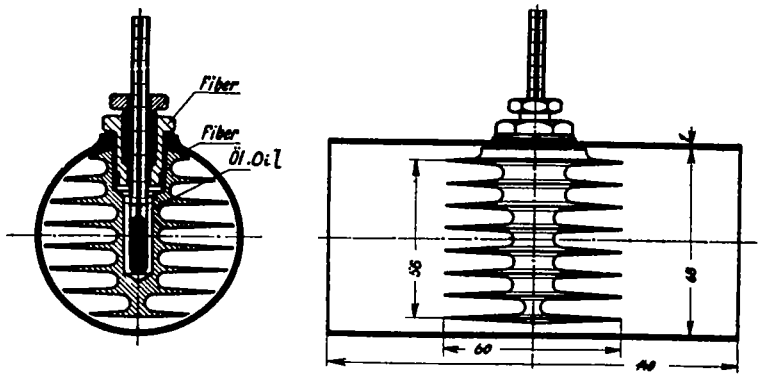


Figure 3.- Finned thermometer cup for mercury thermometer.

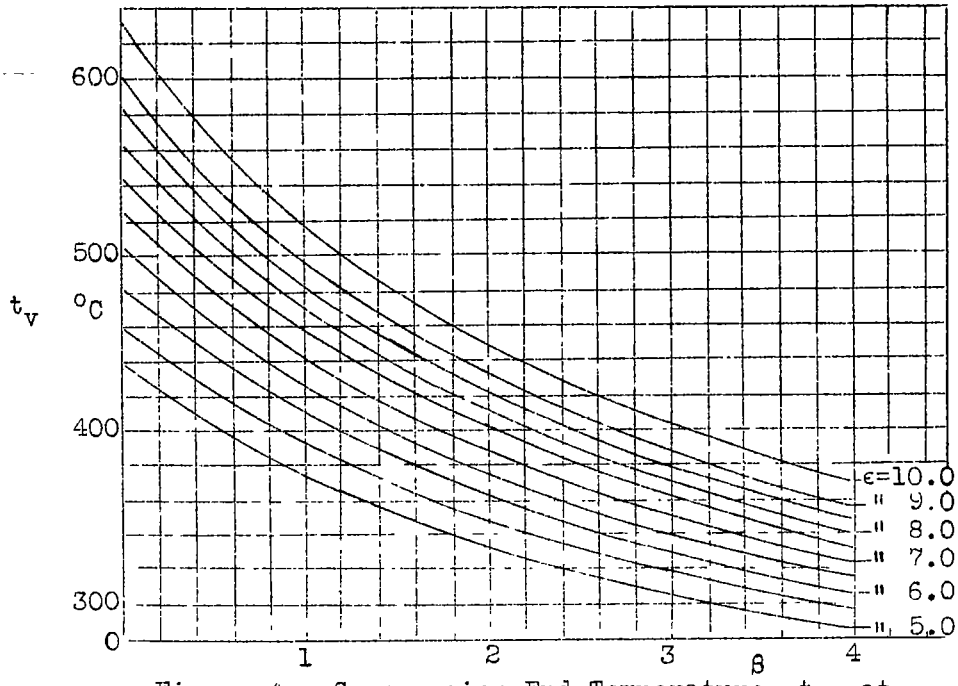


Figure 4.- Compression End-Temperature, t_v, at 140° initial temperature against mixture strength β for ε = 5.0 to 10.0. True compression ratio - see text.

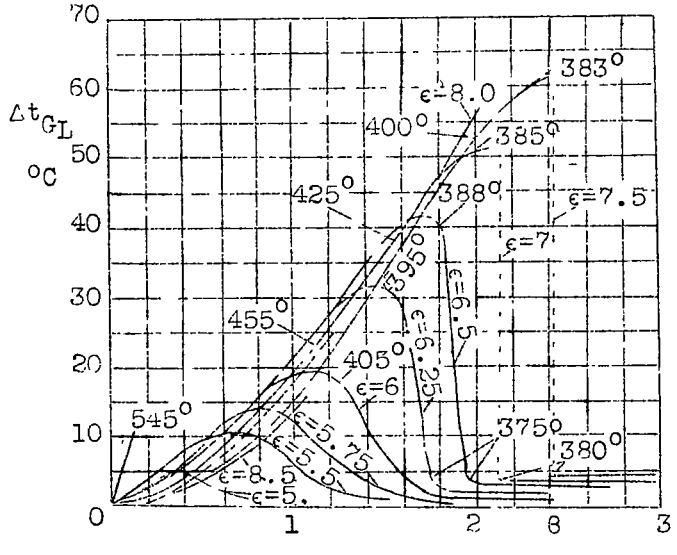


Figure 5.- Behaviour of Fuel No.3 (Aviation Spirit, rated 87-octane). (octane rating 87)

Δt_{GL} = f (β)
n = 1800 rpm
t_{Ge} = 140°C
t_K = 140°C

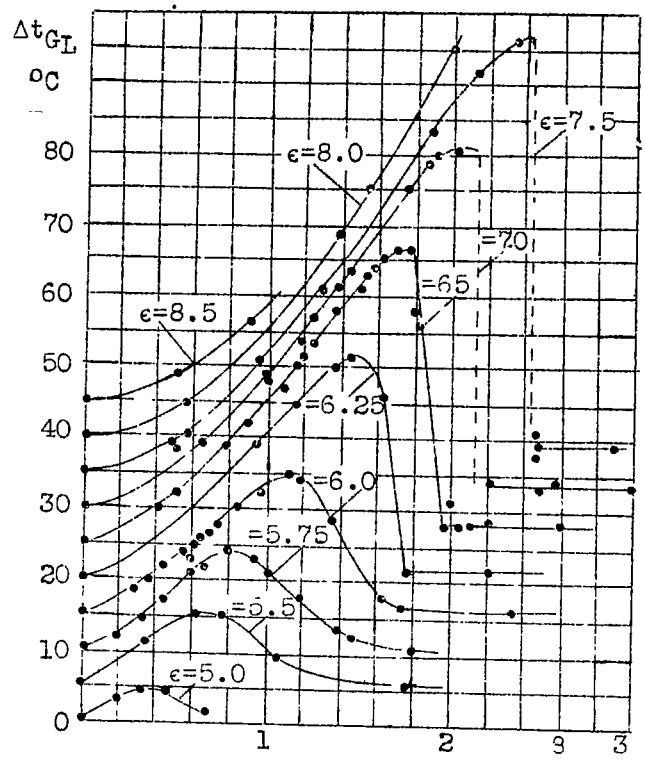


Figure 6.- Behaviour of Fuel No.3: Extended diagram. The curves are parallely displaced upwards for clarity of representation; actually they are commenced at the coordinate origin.

(octane rating 87)
Δt_{GL} = f (8)
n = 1800 rpm
t_{Ge} = 140°C
t_K = 140°C

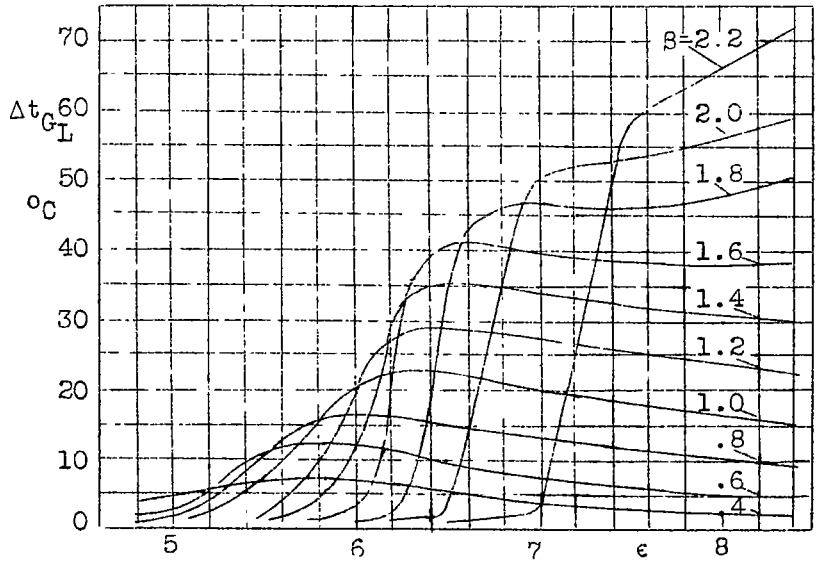


Figure 7.- Behaviour of Fuel No.3. Replotted from Fig,5.

(octane rating 87)
Δt_{GL} = f (ε)
n = 1800 rpm
t_{GL} = 140°C
t_K = 140°C

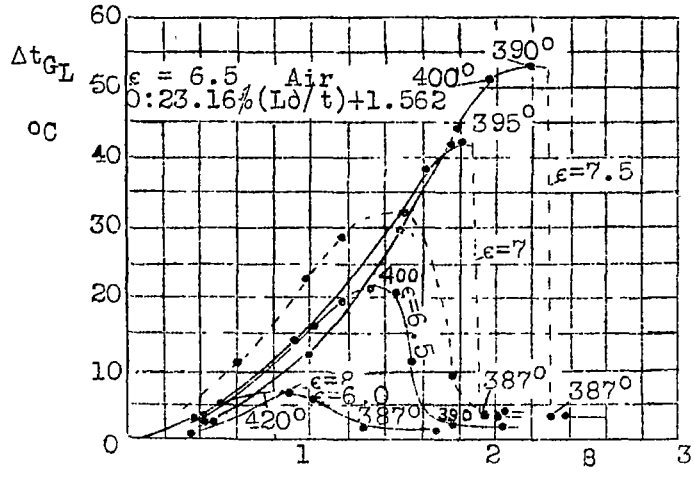


Figure 8.- Behaviour of Fuel No.5. (octane rating 90.6)

Δt_{GL} = f (β)
n = 1800 rpm
t_{Ge} = 140°C
t_K = 140°C

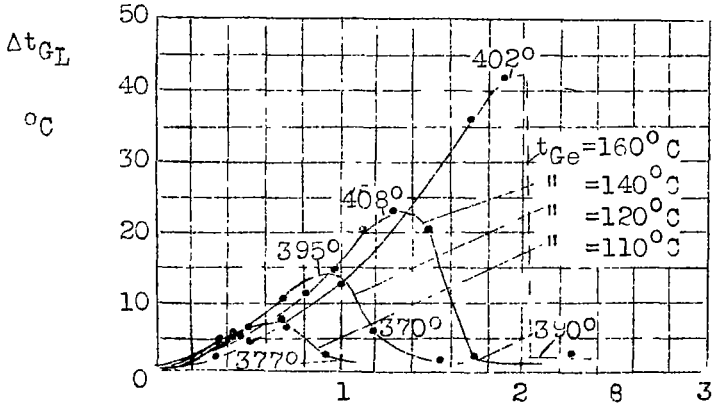


Figure 9.- Behaviour of Fuel No.5. with variable mixture intake temperature. (octane rating 90.6)

Δt_{GL} = f (β)
n = 1800 rpm
t_K = 140°C
ε = 6.5

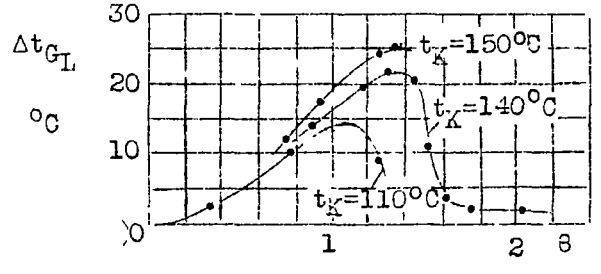
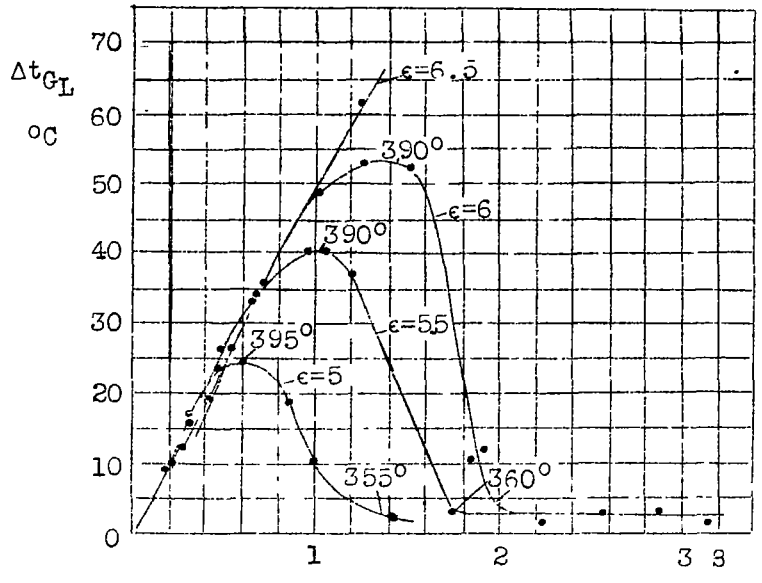


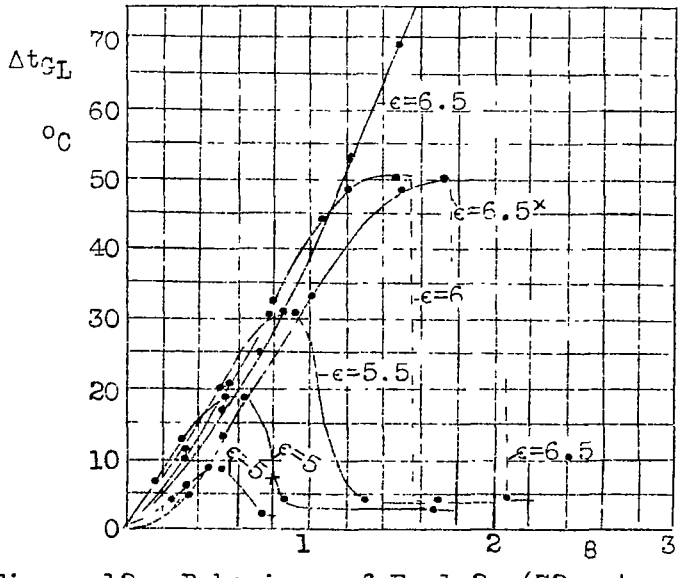
Figure 10.- Behaviour of Fuel No.5 with variable coolant temperature. (octane rating 90.6)

Δt_{GL} = f (β)
n = 1800 rpm
ε = 6.5
t_{Ge} = 140°C



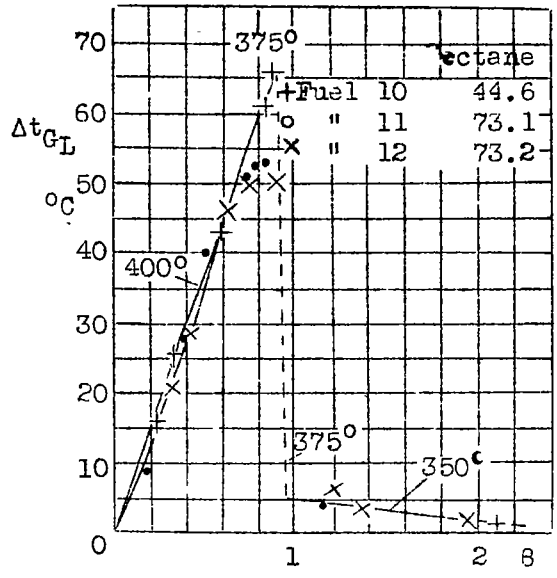
Δt_{GL} = f (ϑ)
n = 1800 rpm
t_{Ge} = 140°C
t_K = 140°C

Figure 11.- Behaviour of Fuel No.1.
(Octane rating 56.4)



Δt_{GL} = f (ϑ)
n = 1800 rpm
t_{Ge} = 140°C
t_K = 140°C

Figure 12.- Behaviour of Fuel 2. (72-octane rating), for $\epsilon = 6.5^x$ and $\epsilon = 5^x$ - Fuel No.13 (87.8 - octane rating) prepared from Fuel No.2 by the addition of 1.3 cm^3 ethyl fluid per litre.



Δt_{GL} = f (8)
n = 1800 rpm
t_{Ge} = 140°C
ϵ = 5
t_K = 140°C

Figure 13.- Behaviour of Fuel No. 10 (44-6 octane rating, I.G. standard reference petrol): and Fuel No.10 with the addition of tetraethyl lead (Fuel No.11, 73.1 octane, and No.12, 73.2 octane).

Δt_{GL} = f (8)
n = 1800 rpm
t_{Ge} = 140°C
t_K = 140°C

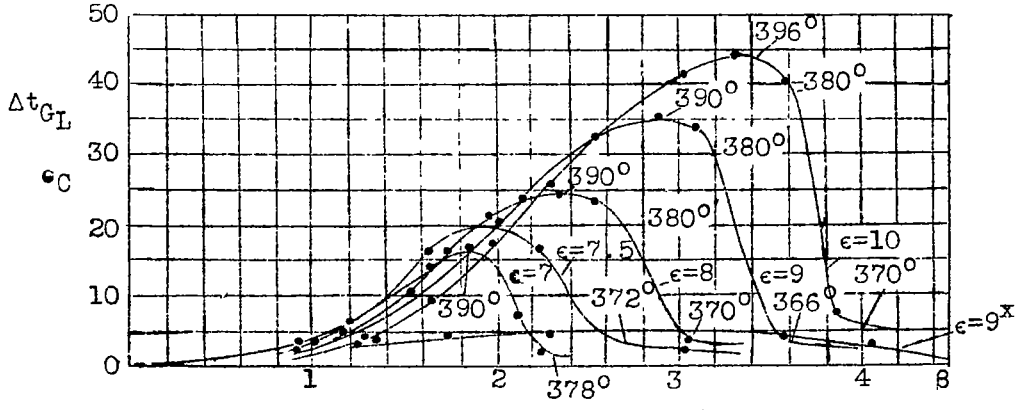


Figure 14.- Behaviour of Fuel No.7 (iso-octane), for $\epsilon = 9^X$ - special 100 octane fuel (No.6).

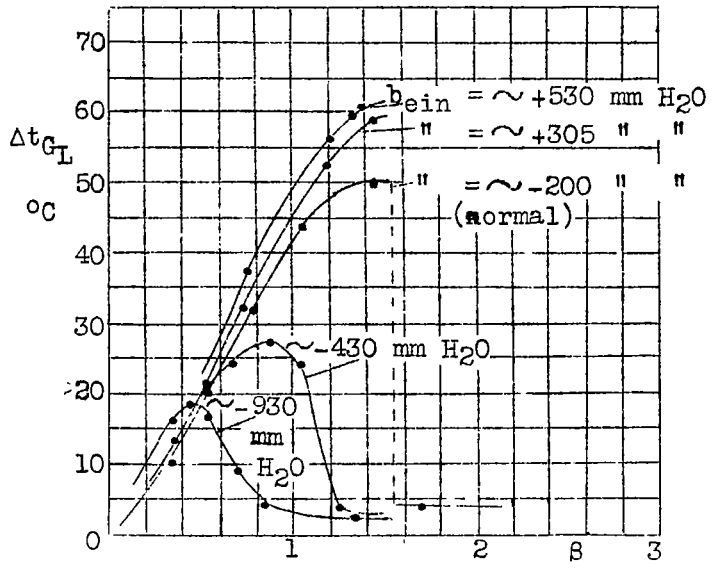


Figure 15.- Relationship of the preliminary reactions to the pressure in the intake pipe (Fuel No.2)
b_{ein} = negative pressure in the intake pipe, mm water, (octane rating 72)

Δt_{GL} = f (ϑ)
n = 1800 rpm
t_{Ge} = 140°C
t_K = 140°C
ε = 6.0

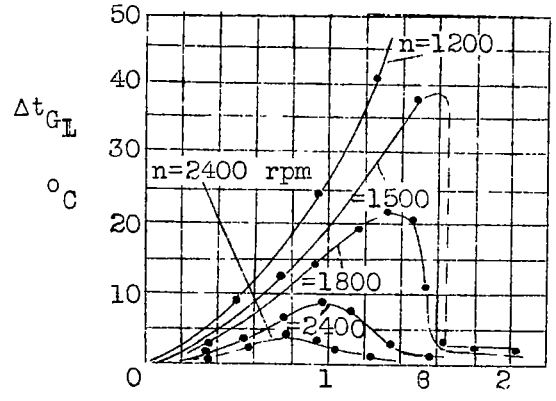


Figure 16.- Influence of engine speed on preliminary reactions (Fuel No.5).(octane rating 90.6)

Δt_{GL} = f (ϑ)
ε = 6.5
t_{Ge} = 140°C
t_K = 140°C

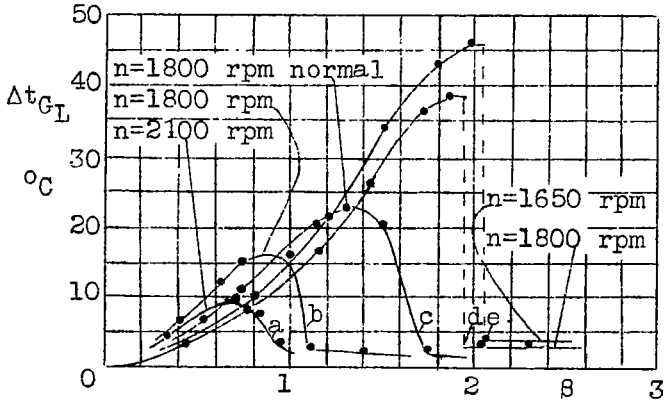
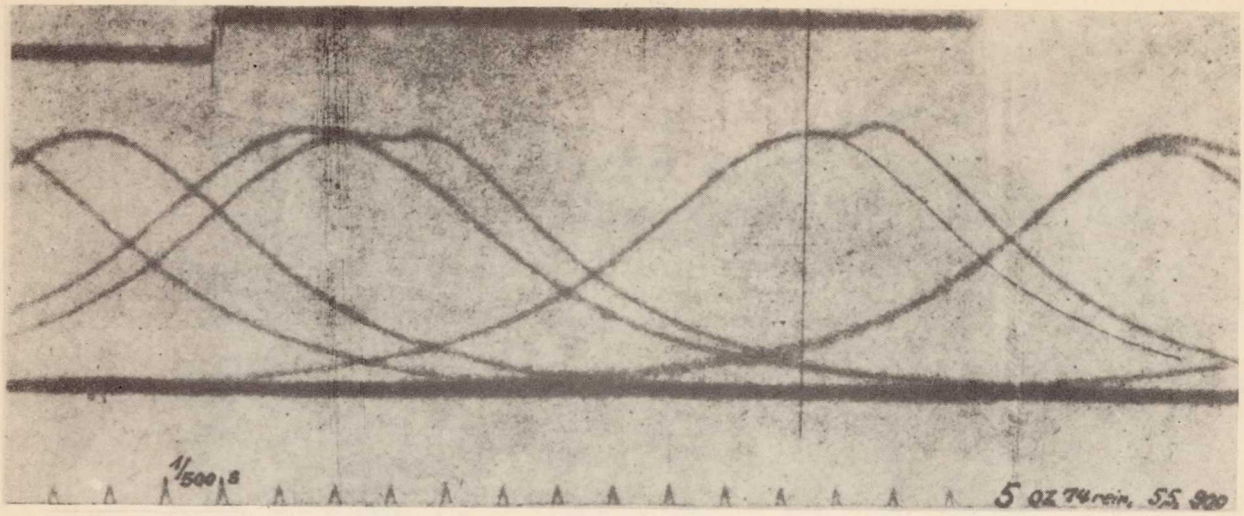


Figure 17.- Influence of engine working conditions on preliminary reactions (Fuel No.5). (octane rating 90.6)

Δt_{GL} = f (ϑ)
ε = 6.5

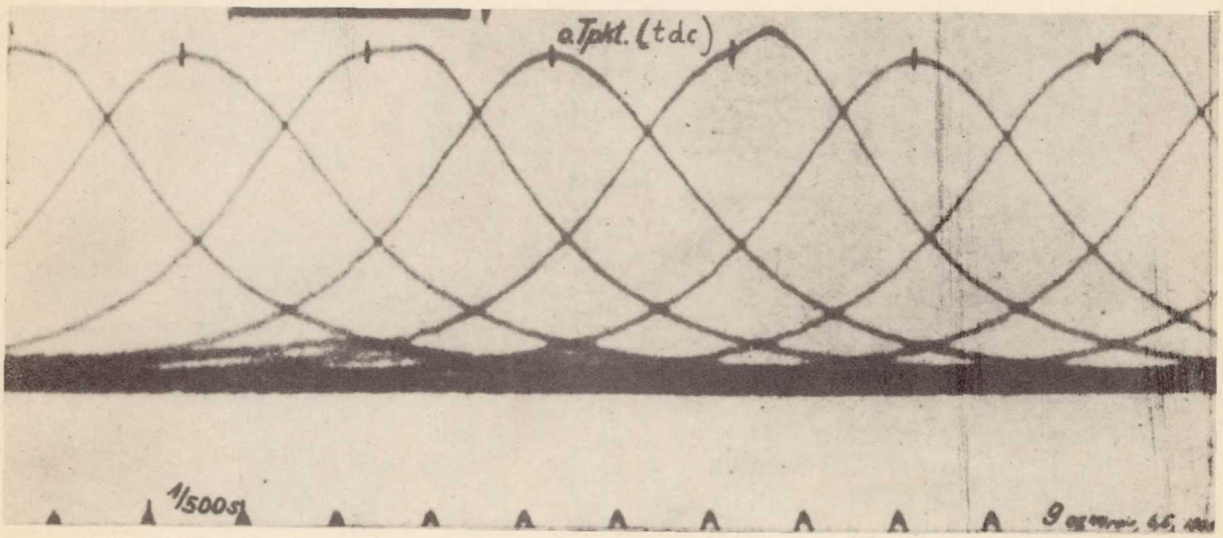
a: t_{Ge} = 120°, t_K = 120°
b: t_{Ge} = 120°, t_K = 120°
c: t_{Ge} = 140°, t_K = 140° normal
d: t_{Ge} = 150°, t_K = 150°
e: t_{Ge} = 150°, t_K = 150°



Engine speed - n = 900 rpm
Compression ratio - ϵ = 5.5
Mixture strength - β = 1.0
Δt_{GL} = 27 °C

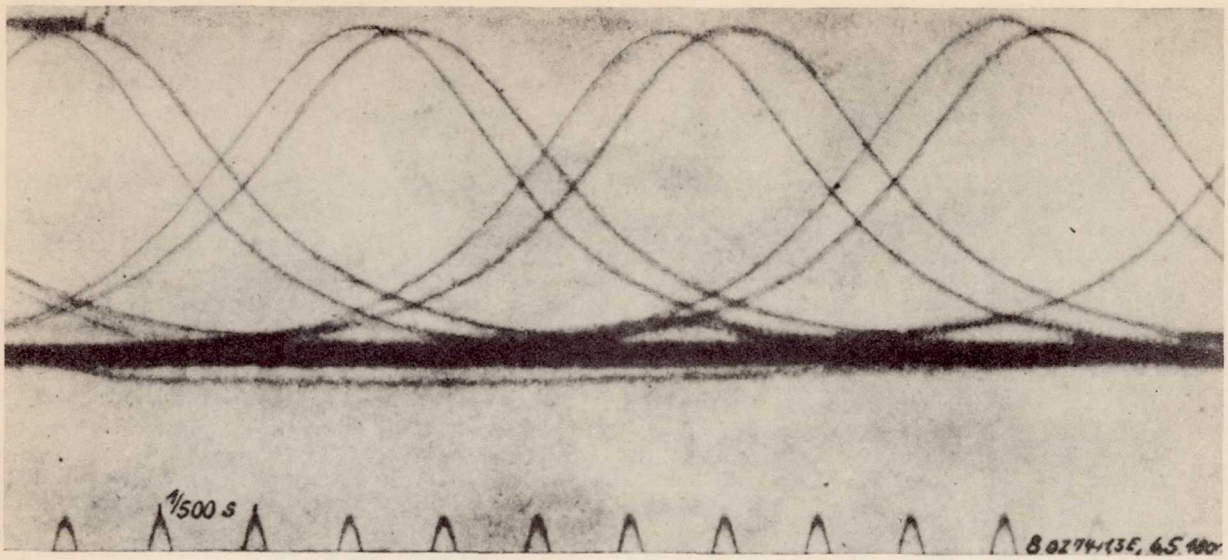
Figure 18.- Pressure-time diagram for fuel No.2 (unleaded, 72-octane rating).

In one diagram a perpendicular has been erected through the T.D.C. and the mirror image of the compression line plotted next to the expansion line, to show the effect of the preliminary reactions on the pressure-rise.



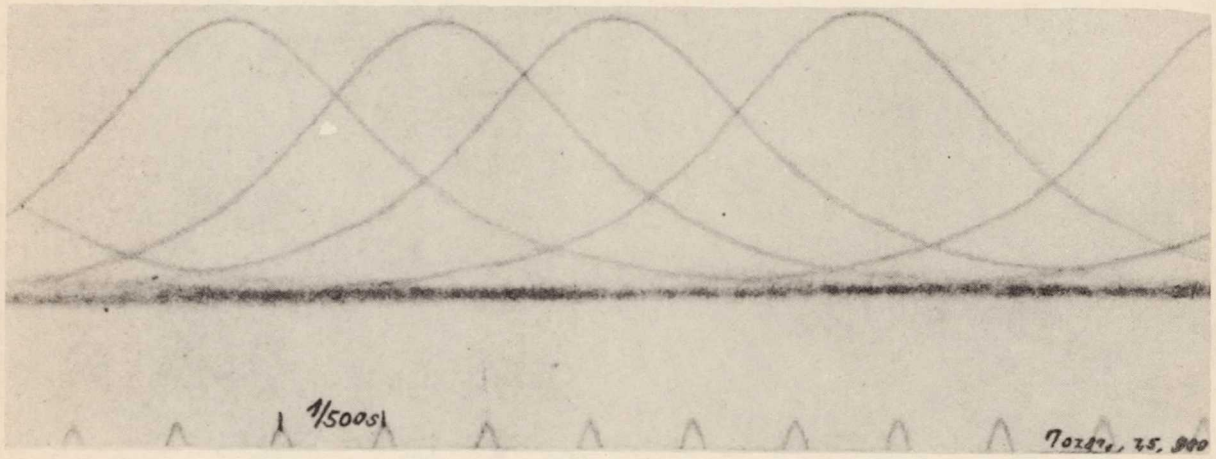
Engine speed - n = 1800 rpm
Compression ratio - ϵ = 6.5
Mixture strength - β = 1.59
Δt_{GL} = 50.5 °C

Figure 19.- Pressure-time diagram for fuel No.2 (unleaded).



Engine speed - n 1800 rpm
Compression ratio - ϵ = 6.5
Mixture strength - β = 1.4
Δt_{GL} = 50 °C

Figure 20.- Pressure-time diagram for fuel No. 13 (prepared from fuel No. 2 by leading).



Engine speed - n 900 rpm
Compression ratio - ϵ = 7.5
Mixture strength - β = 1.93
Δt_{Gl} = 59 °C

Figure 21.- Pressure-time diagram for fuel No. 3 (leaded).

Owing to the leading, the characteristic peaks in the expansion line in Figs. 18 and 19, will be noted to have disappeared in the two figures above.

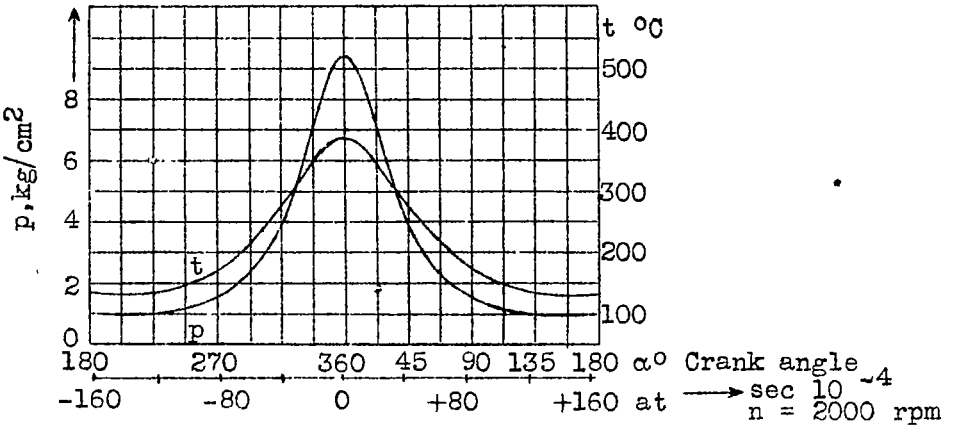


Figure 22.- Pressure and temperature curves for the diagram Fig. 19 (third diagram from the right) calculated for n = 1800 rpm. Pressure-time, temperature-time, and valve-fixing diagrams, see text.
$\epsilon = 6.5 \quad \beta = 1.59 \quad \omega \quad 1.60$

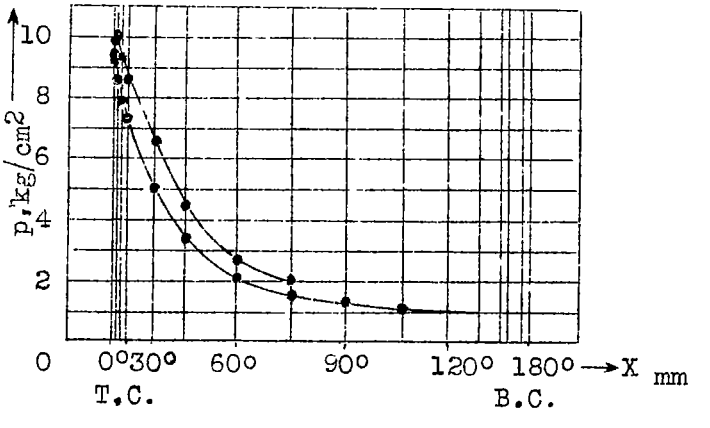


Figure 23.- Pressure-path diagram for the above.

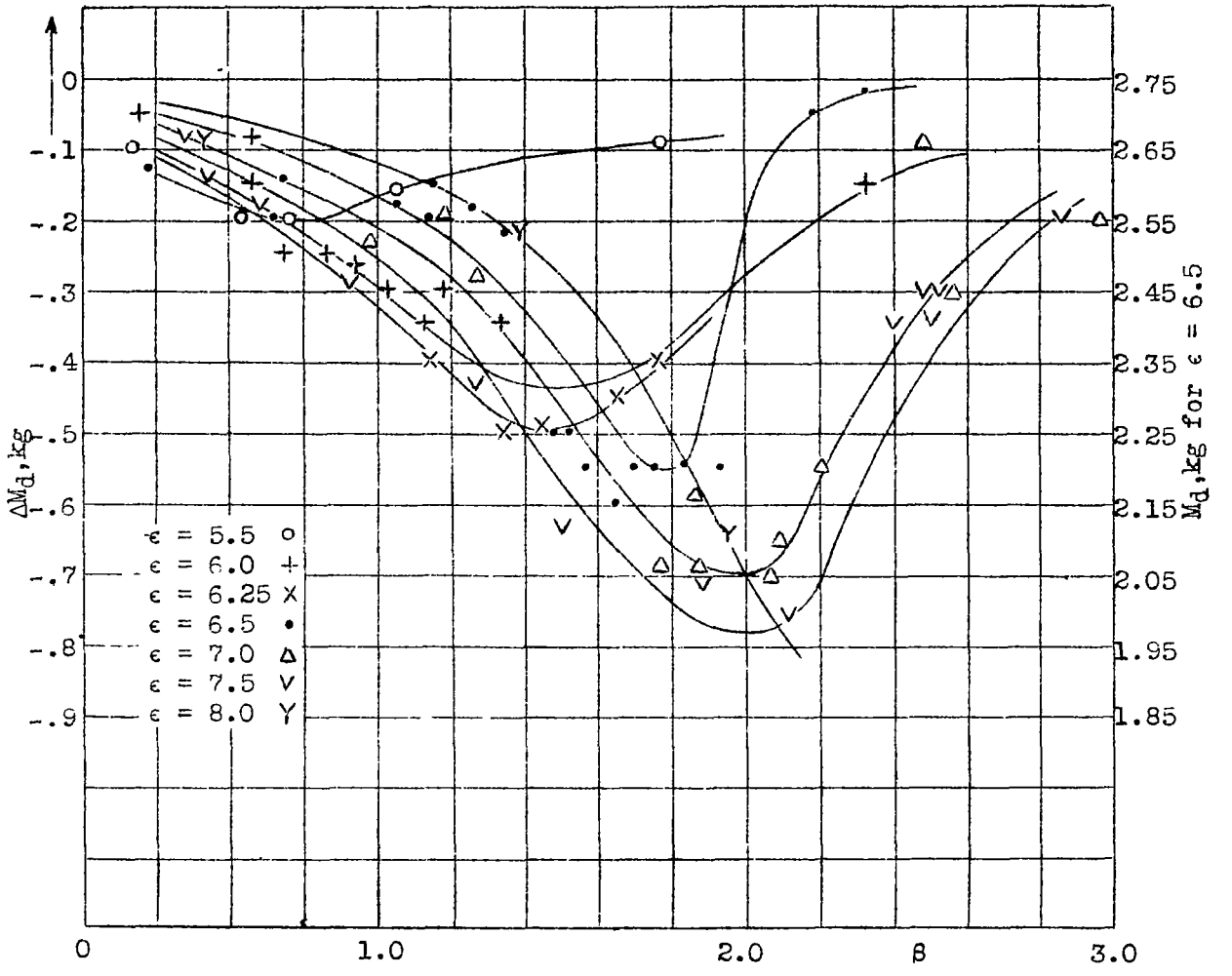
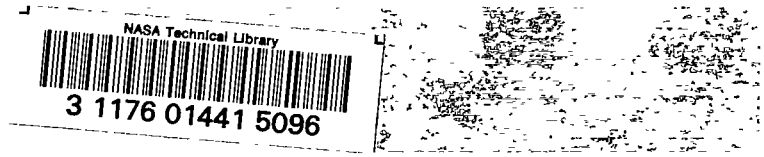


Figure 24.- Free torque curves (ΔM_d) against β, for Fig. 5.
Fuel No. 3. (octane rating 87)
$\Delta M_d = f(\beta)$
n = 1800 rpm
t_{Ge} = 140° C
t_K = 140° C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